the Acid Deposition Research Program

BIOPHYSICAL RESEARCH

EFFECTS OF ACID DEPOSITION ON SOILS IN ALBERTA

by:
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EXECUTIVE SUMMARY

The potential impact of acid deposition on the soils of Alberta has been of concern in this province for at least the last decade. This concern is related to the possible short- or long-term effects that acid deposition might have on the productivity of agro- or forest ecosystems. There has also been a concern that acidic or acid forming substances from the atmosphere that are deposited on the land surface might eventually find their way into water bodies, leading to the acidification of aquatic ecosystems as well. The objective of this report is to provide a review of the current scientific literature which reflects the present state of knowledge of the effects of acid deposition on soils and to relate that literature to the soils of Alberta. More specifically, the objectives of this report are:

1. to describe and discuss present concepts of the nature of soil acidity;
2. to describe and discuss the influences of acidity from both natural and anthropogenic sources on soil attributes including pH, ion exchange properties, nutrient availability, biogeochemical cycling, and the solubility and availability of toxic chemical constituents, particularly aluminum;
3. to describe the major soils of Alberta in terms of genesis and classification, chemical and physical properties, and their distribution and extent; and
4. to evaluate the potential impact of the deposition of varying levels of acidic and acid-forming substances on agricultural and forest soils with emphasis on the potential changes in soil properties, effects on biogeochemical cycles and on the acid neutralizing capacity of soils.

The nature of soil acidity, including its chemistry, natural sources, and its role in soil genesis, is discussed in Section 2. The components and forms of soil acidity, as well as the factors affecting it, are reviewed. The intensity of acidity is indicated by the soil pH or lime potential while resistance to change in these depends on the buffering capacity. The cation exchange capacity and acidity of soils are interrelated. The concentrations of base cations, which are essential plant nutrients, and of aluminum, which can be toxic to plants, are dependent on the interactions between acidity and the exchange complex. These interactions are complex, but their elucidation is essential for predicting and understanding the possible impacts of acid deposition on soils.

The influence of soil acidity and acidification on other soil properties is discussed in Section 3. Organic matter is a component which affects other soil properties to an extent which far exceeds its content in the soil. It contributes to cation exchange capacity, influences soil pH through buffering, chelates and complexes metal and base cations, and forms organo-mineral particles and aggregates. All plant nutrients cycle through the organic matter pool to a greater or lesser extent. The most commonly predicted effects of acid deposition on organic matter are reduction in the rate of decomposition, changes in nutrient cycling in ecosystems, and possible deterioration of soil structure.

Acidification of soils involves the displacement of basic cations from exchange surfaces, their replacement by H^+ and Al^{3+} ions, and establishment of new exchange/solution equilibria. The base cations may then be removed from the soil by leaching. However, in some soils the pH and base saturation may decrease with no corresponding net nutrient loss. Soils rich in Fe and Al hydrous oxides exhibit a substantial capacity to adsorb SO_4^{2-} and must retain H^+ as well as base cations in order to maintain charge balance in the soil solution. Few Alberta soils have significant contents of hydrous oxides; consequently, most soils could be highly susceptible to accelerated leaching losses of base cations due to acidic inputs. The extent of base loss can vary greatly among soils. Numerous published studies in which soils have been leached with simulated acid precipitation have indicated negligible changes in soil pH and cation levels unless the precipitation pH was about 3 or lower. There nevertheless is concern about base loss because short-term experiments do not necessarily simulate long-term acidic deposition.

The plant availability and potential toxicity of elements such as aluminum, lead, zinc, copper, and cadmium is dependent on the pH of the soil. Soil acidification, accelerated by acid deposition, may result in increased solubilization of aluminum and heavy metals and possibly create phytotoxic conditions for plants. These elements can also be leached out of the soil and eventually move downward or laterally to groundwater, lakes, and streams. Aluminum toxicity has been implicated in dieback of forests in West Germany.

Acidic deposition can have various effects on the macronutrients nitrogen, sulphur, and phosphorus. Nitrification, or oxidation of NH_4^+ to NO_2^- and ultimately to NO_3^-, may be the process of the nitrogen cycle most susceptible to increased acidity. Sulphur from acid deposition may be beneficial to plant growth. Where sulphur is deposited in excess of vegetation requirements and soil adsorption capacity, leaching of SO_4^{2-} and associated cations may occur. The predicted effect of acidification on soil phosphorus is that as the rate of microbial turnover decreases, organic phosphate will accumulate. Fixation of most major nutrients may result if microbial activity is significantly reduced by increased acidity. In calcareous soils the addition of acidic substances could result in solubilization of calcium phosphates, and higher P levels in solution will be available to plants or be removed by leaching.

Chemical weathering of primary minerals is largely accomplished by hydrolysis. Weathering is accelerated by increased acidity but counteracts acidification due to consumption of H^+ in the process. The quantities of weatherable minerals in Alberta soils are generally quite high and, therefore, they represent a very large capacity to counteract acidity. Other factors which retard or neutralize acidity include the high lime levels in many Alberta soils, introduction of acid neutralizing substances through dustfall, and entrainment or solution of basic substances in precipitation. The capacity of each of these processes to neutralize acidity is high in the plains region of Alberta and the other western provinces as compared with areas such as eastern North America.

Effects of different anthropogenic sources of acidity on soils are discussed in the latter part of Section 3. The acidifying influence of nitrogenous fertilizers has been the subject of a number of reports in recent years in Alberta and elsewhere. Large reductions in soil pH as a consequence of fertilization have been reported in Alberta.

Lime application is becoming increasingly necessary to restore soils to suitable fertility levels. In most areas the acidification of soils due to fertilization is much greater than that resulting from acid deposition. The general consensus from reports in various parts of the world is that liming practices required to counteract effects of fertilizers will more than compensate for acidity from atmospheric sources. It would appear that the only area of concern regarding acidification of agricultural soils by atmospherically deposited acidic substances are situations where soils are highly sensitive, where the soils are subjected to high deposition rates due to proximity to emitters, and where agricultural soils are minimally managed and not fertilized or limed.

The different types of atmospheric deposition are briefly reviewed in the latter part of Section 3. Dry deposition is considered to be the major process in Alberta. The fate of SO_2 and NOx upon contacting soil surfaces does not appear to be well understood. A number of studies have been carried out in Alberta in which high levels of S adsorbed by both bare and vegetated soil surfaces were observed. However, little of the S was found in sulphate form. Little is known about the mechanisms of sulphur interactions and of resulting sulphur forms in soils. Knowledge of these mechanisms and forms is necessary for determining the actual acidifying influences on soils.

An overview of the development, properties, distribution and use of soils in Alberta is presented in Section 4. Soils of all nine orders described in the Canadian system of soil classification are found in Alberta. Chernozemic, Solonetzic, Luvisolic, Brunisolic, and Organic soils occupy the largest areas. Gleysolic, Regosolic, Podzolic, and Cryosolic soils are less extensive but nevertheless account for a considerable area of the province. Each of the soil orders is described in terms of properties such as acidity, exchange properties, mineralogy, geochemistry, and bioelement characteristics. Examples of representative profiles are provided. In addition to demonstrating specific properties of soils, these serve the purpose of providing examples for modelling acid deposition impacts in the following section.

Potential impacts of acid deposition on Alberta soils are discussed in Section 5. The sensitivity rating scheme developed for Alberta, in which soils are rated as having low, moderate, or high sensitivity to acidification, is initially summarized. In addition to sensitivity, the neutralizing capacity of soils is evaluated in this scheme.

A semiempirical model for predicting soil response to acidification which was developed at the University of Minnesota was applied in this report to demonstrate possible impacts on Alberta soils. The model predicts changes in pH, base saturation, and soluble Al content over time for given inputs of wet and dry deposition. It is based on relationships between pH and base saturation, on Al solubility and on CO_2 content of soil. Simulations using the model provide an effective means of quickly predicting response over time and for comparing responses among different soil types. Simulations were carried out on examples of Chernozemic, Solonetzic, Luvisolic, and Brunisolic soils. At an acid input level of 0.1 kilomole of H^+ per hectare per year ($\sim$1 kg S ha^{-1} y^{-1}), changes in pH, base saturation, and Al were predicted to be minimal, even after 100 years. Only very sandy soils with low clay and organic matter contents showed a significant response within 100 years in the simulation. Most soils displayed a significant response to acid loadings of 1 kilomole per hectare per year (~15 kg S ha^{-1} y^{-1}). Base saturation and pH dropped significantly in coarse textured soils within 100 years, and in finer soils after about 200 or 300 years. Solution Al concentrations increased in all soils and were highest in Brunisolic and Luvisolic soils which initially were highly acidic. A simulation with one soil receiving an acid loading of 3 kilo-mole per hectare per year (~50 kg S ha^{-1} y^{-1}) predicted substantial drops in pH and base saturation, and an increase in Al content within 100 years. Various assumptions were made in this modelling exercise and the resulting responses are considered to be much more severe than could realistically be expected.

The modelling results confirmed that the soils which are most likely to be strongly affected by acid deposition are coarse textured mineral soils with surface horizons which are already strongly acidic. These latter soils occur mainly in the Luvisolic, Brunisolic, and Solonetzic orders. The model could not be applied to Organic soils, but an evaluation based on various reports indicates that those of moderate acidity and low nutrient content have low buffering capacity and are, therefore, highly susceptible to changes due to acid deposition.

General conclusions and recommendations are presented in Section 7 of the report. The main recommendations are summarized below.

It is recommended that soil acid deposition effects be investigated by modelling because of the capability it provides for synthesizing information, identifying research needs, and predicting impacts. Models are required for soil response studies, but these should be developed primarily for interfacing with soil-plant response models and, via water and solute transport models, with lake-watershed acidification models. Recommendations for modelling, listed in order of precedence, are that:

1. acid deposition impacts on soils be investigated by modelling and that a literature review and evaluation of models applicable to Alberta soils be undertaken;
2. research be carried out wherever insufficient information is available for developing model inputs;
3. model simulations be carried out and performance be evaluated through field and laboratory studies; and
4. current soil sensitivity ratings be evaluated and updated by application of the model.

A second group of recommendations addresses the need to improve the knowledge and information base about acid deposition impacts on soils. These recommendations have different priorities, as indicated in Section 7, but there is no required order of precedence. It is recommended that:

5. research into SO_2/NOx-soil interactions be undertaken;
6. research on acid deposition impacts on soil acidity, base status, and related soil chemical properties be undertaken;

7. solubilization and movement of Al and other toxic elements in soil be investigated in relation to acid deposition;
8. research into biogeochemical cycling in ecosystems be carried out; and
9. research on soil moisture regimes in relation to acid deposition and leaching effects be conducted.

Recommendations of a third group, which address needs with regard to different kinds of soils, are that:

10. priority for research be given to soils considered to be highly sensitive;
11. research into the effects of fertilizer practices on acidification of soils be continued; and
12. research on acid deposition effects on peatlands be carried out.

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1. INTRODUCTION

The acidification of soils is one aspect of the effects of acid deposition on the terrestrial ecosystem that has caused considerable concern in various parts of the world in recent years. The concern and consequent studies have mainly focussed on the acid forest soils of Scandanavia, northern Europe, northeastern United States and southeastern Canada. Reasons for the concern have related mainly to the possibility of reduced forest productivity and to the role of soils in stream and lake acidification. Interest about the impact of atmospheric acid deposition has been expressed in relation to the possibility of reduced productivity in agricultural soils as well. Reports of severe effects occurring in forest soils of eastern Canada and the United States have generated concern about effects on soils in Alberta even though the acid loadings are evidently much lower than in the more populated and industrialized eastern regions of the continent.

The question of the nature and extent of acid deposition effects on soils is a controversial one. Convincing evidence for deleterious effects of acid inputs on soils and forest or agricultural productivity is scant. It has been argued that the acidification of soils and lakes in the eastern United States has not been the consequence of atmospheric acid deposition as much as of changes in land use over the past several decades (Krug and Frink 1983a). With regard to agricultural soils, a commonly expressed opinion is that effects will be insignificant because cultivated soils are predominantly well buffered. Moreover, the acidifying influence of fertilizers is generally much greater than that of atmospheric acidic inputs. The consequent necessity for liming farmed soils renders any concern about atmospheric deposition unnecessary. The issue is further complicated by the possibility that the major acidifying components of atmospheric deposition, namely SO_2 and NO_x, are plant nutrients and may therefore be beneficial to crop or forest growth. It has been suggested that no severe effects can be expected in the province of Alberta because of the low sulphur loading in atmospheric deposition (Sandhu et al. 1980). However, there is insufficient evidence to either substantiate or refute the possibility of harmful impacts by long-term, low level deposition of acid forming substances (Legge 1980). The impact of deposition on soils near emitters or point sources may be greater than on soils under ambient depositional conditions but there also is little knowledge of these. In Alberta there is insufficient information concerning the proportions of acid deposition due to dryfall and to wetfall. There is likewise insufficient understanding of the interactions of these different forms with soil.

The general objective of this report is a review of the literature which reflects the present state of knowledge of the short- and long-term effects of acidic and acid forming substances from the atmosphere on soils, with particular emphasis on relating that literature to Alberta agronomic and forest ecosystems. The present concepts of the nature of soil acidity and related soil properties are initially discussed. The influences of soil acidity and of atmospheric acid deposition on soil properties including changes in pH, acid neutralizing capacity, ion exchange properties, organic matter, biogeochemical cycling, nutrient and toxic element availability, and others are discussed in the following section. The interactions of soil with acidic and acid forming substances from the atmosphere are then briefly reviewed. There is a wide variety of soils in Alberta, a feature which poses great difficulties in assessing the effects of acidic deposition in the province. This diversity is revealed through an overview of the types, properties, and distribution of soils in Alberta. The overview also has the purpose of establishing a framework for discussion and extrapolation of possible effects of acid deposition on soils.

The potential impacts of the deposition of varying levels of acidic and acid forming substances on soils in Alberta are presented in the last major section of this report. A simple modelling approach is used to demonstrate potential changes in acidity, ion exchange properties, and Al contents in a few representative profiles of the major soil orders. Soil sensitivities are briefly discussed along with qualitative assessments of impacts on other soil properties. A summary of conclusions and recommendations for further work are presented in the final sections of the report.

2. NATURE OF SOIL ACIDITY

2.1 THE CHEMISTRY OF SOIL ACIDITY

2.1.1 General Concepts

The Bronsted-Lowry concepts of acids and bases are commonly applied to the study of soil acids and bases (van Breemen et al. 1983). According to these concepts, an acid is a substance that can donate a proton while a base is a substance that can accept a proton. A proton donor and the acceptor of that proton are termed a conjugate acid-base pair; examples of conjugate acid-base pairs in soil systems include H_3O^+-H_2O, $Al(OH)_2^+$-$Al(OH)_3$, H_2CO_3-HCO_3^-, and NH_4^+-NH_3 (van Breeman et al. 1983).

The soil is made up of many acid-base systems. The strength of acid-base systems (conjugate acid-base pairs) is measured by the proton dissociation constants (K_{HA}).

$$HA + H_2O = H_3O^+ + A^- \; ; \; K_{HA} = (H_3O^+)\,(A^-)/(HA) \qquad [1]$$

$$pH = pK_{HA} + \log\,[(A^-)/(HA)] \qquad [2]$$

When the acid system is strong, the dissociation of protons is increased and the value of K_{HA} is greater; the pK for an acid is the pH value at 50% dissociation where $(A^-) = (HA)$.

Soil acidity is best considered in terms of intensity and capacity factors. Capacity factors are a function of the size or quantity of the system, are directly influenced by addition or depletion of protons, and are characterized by the amount of base needed to titrate the soil to a set endpoint. Intensity factors (such as pH) are a function of the chemical properties of the system, and are independent of the quantity of the system (van Breemen et al. 1983). According to Bache (1980a), there are three parameters included in defining soil acidity: the total acidity, the degree or intensity of acidity, and the buffer capacity or the manner in which the degree of acidity varies with the total acidity.

2.1.2 Soil Reaction

The degree of acidity (an intensity factor) is related to the number of free hydrogen ions in solution, which probably exist as the hydrated forms H_3O^+ and $H_7O_3^+$ (Bohn et al. 1979). These ions can be the product of dissociation of weak acids, as shown in the previous section. The degree of acidity is usually represented by a pH value which has the following "quasi-thermodynamic" definition (Bache 1979a):

$$pH = -\log a_H \qquad [3]$$

Where a_H is the thermodynamic activity of the hydrogen ion, and is related to the concentration m (moles litre^{-1}), by the activity coefficient x ($a_H = mx$). Measurements of pH values of solutions are accomplished through the use of colour changes in pH indicator dyes or potentiometric measurement using glass and calomel electrodes (Bates 1973).

Soil pH measurements are performed routinely for most soils, and are used to assess the acidity and fertility status (Black 1968). The pH concept discussed above applies to solutions only. Soils are mixtures of porous charged solids and humus with little solution, making it impossible to define theoretically or determine experimentally a unique pH value (Bache 1979a). Measured soil pH values are found to depend on the following variables: drying of the soil, soil-to-water ratio, CO_2 concentrations in equilibrium with the soil suspension, and solution electrolyte concentration (Jackson 1958). Air drying of acid or calcareous soils generally leads to a rise in measured pH values (Jackson 1958). Dilution of the soil suspension (increasing the soil-to-water ratio) leads to an increase in the pH value; there could be a rise as high as 1 pH unit in going from a suspension at the "sticky point" of a soil to one at a ratio of 1:5 (Peech 1965). The effect of increasing the CO_2 concentration in equilibrium with a soil suspension leads to a decrease in soil pH. This effect is not very significant for soils in equilibrium with CO_2 in the air and whose pH values are lower than 7 (Peech 1965). Increasing the electrolyte concentration of the soil solution causes a decrease in soil pH. This effect is similar but opposite to that of dilution of the soil suspension and is due mainly to the exchange reactions of H^+ and other basic cations such as Ca^{2+} and Mg^{2+} (Thomas and Hargrove 1984). Difficulties in obtaining soil pH measurements led some to the use of other variables not affected by the above parameters, such as the lime potential of Schofield and Taylor (Bache 1979a), or the adoption of standard methods for pH measurements that are made at unique soil-to-water ratios and salt concentrations (Peech 1965).

Soil pH measurements are mainly conducted potentiometrically in dilute electrolyte suspensions but these can be problematic because values vary with the position of the calomel electrode in the suspension (Black 1968). Lower pH values are obtained when the calomel electrode is inserted into the sediment than if inserted into the overlying supernatant, while the position of the glass electrode does not affect the pH measured. This has been termed the "suspension effect" and is thought to originate from an extra junction potential in the calomel electrode due to the effect of charged surfaces on the mobility of K^+ and Cl^- ions out of the calomel electrode (Thomas and Hargrove 1984). Suspending the soil in an electrolyte solution ($CaCl_2$ or KCl) of ionic strength > 0.005 M will eliminate the "suspension effect" (Bache 1979a).

2.1.3 Lime Potential

Due to the uncertainties in measurements of soil pH as caused by the suspension effect and electrolyte concentration, Schofield and Taylor (1955) proposed that pH be measured in the supernatant of soil suspended in 0.01 M $CaCl_2$. They expressed their result as pH - 1/2 pCa, where pCa is the negative logarithm of the Ca^{2+} activity in solution; that term was called "lime potential" because it is equivalent to the mean activity of $Ca(OH)_2$. It was proposed that the lime potential is independent of electrolyte concentration, which is generally true for the concentrations encountered in soils (Hargrove and Thomas 1984).

In calcareous soils, the following reactions are responsible for determining the activities of H^+ and Ca^{2+} ions in soil solution (Talibudeen 1981):

$$[CO_2]soln = k_H \, pCO_2 \qquad [4]$$

$$H_2O + [CO_2]soln = H_2CO_3 = [H^+] + [HCO_3^-] = 2[H^+] + [CO_3^{2-}] \qquad [5]$$

$$CaCO_3 = [Ca^{2+}] + [CO_3^{2-}] \qquad [6]$$

Taking the equilibrium constants of the above reactions and their relationship to the activities of Ca^{2+} and H^+, one obtains the equation

$$2pH - 1/2 \, p[Ca^{2+}] + \log pCO_2 = pk_H + pK_1 + 2pK_2 - pK_{sp} + 1.34(I)^{1/2} \qquad [7]$$

where I is the ionic strength, k_H is Henry's constant, K_1 and K_2 are the acidity constants of H_2CO_3, and K_{sp} is the solubility product of $CaCO_3$. In dilute solutions, the I term in the above equation can be neglected and the right hand side of the equation becomes constant; the lime potential then depends on the partial pressure of CO_2 and temperature in the soil (Talibudeen 1981).

In non-calcareous soils, the activities of H^+ and Ca^{2+} ions are determined to a degree by the following reactions (Thomas and Hargrove 1984; Reuss 1985):

$$Al(OH)_3 + 3H^+ = Al^{3+} + 3H_2O, \text{ and} \qquad [8]$$

$$K_a = (Al^{3+})/(H^+)^3 \qquad [9]$$

$$3CaX + 2Al^{3+} = 2AlX + 3Ca^{2+}, \text{ and} \qquad [10]$$

$$K_g = [(AlX)^2 . (Ca^{2+})^3]/[(CaX)^3 . (Al^{3+})^2] \qquad [11]$$

combining the above equations for K_a and K_g and rearranging,

$$(Ca^{2+})^{1/2}/(H^+) = [(Ka)^{1/2}(Kg)^{1/6}(CaX)^{1/2}]/(AlX)^{1/3} \qquad [12]$$

and taking negative logarithms of both sides

$$pH - 1/2 \, pCa = K_L \qquad [13]$$

where K_L is the lime potential, and is equivalent to the negative logarithm of the right hand side of equation 12. The equation above states that lime potential is proportional to the Al-H proportionality constant (K_a), the exchange constant (K_g), and the exchange sites occupied by Al and Ca.

The usefulness of the lime potential concept is in the fact that soil reaction is the product of the interaction and balance of H^+ ions and other mobile ions, whose relationship is best expressed as the H^+ activity relative to the "reduced ratio" of other cations (Bache 1979a). The other cations include the base cations (Ca^{2+}, Mg^{2+}, and Na^+) in calcareous soils, in addition to Al^{3+} in acid soils, as described earlier in this section.

2.1.4 Soil Buffering Capacity

Bache (1980a) defines the acid-base buffer capacity (b) as the amount of acid (A) or base (B) required to change the pH of the soil by one unit:

$$b = \Delta A/pH = \Delta B/pH \qquad [14]$$

It can also be defined as the resistance of the soil to variation in pH (Gessa 1979).

Buffering in soils is chiefly due to colloidal organic and inorganic materials. Buffering capacity may vary with pH and may also be time dependent as dissolution kinetics vary with composition of the soil. The inorganic colloidal soil complex functions as a slightly ionized acid or a slightly ionized salt of a weak acid. Clays act as weak acids due to exchangeable aluminum which hydrolyzes and exhibits different forms varying with pH as shown by Bache (1980a):

$$Al^{3+} \rightleftarrows Al(OH)^{2+} \rightleftarrows Al_n(OH)_m^{(3n-m)+} \rightleftarrows Al(OH)_3 \rightleftarrows Al(OH)_4 \qquad [15]$$

	mono-nuclear ions	poly-nuclear ions		solid
Approximate pH	3.5	5	6.5	8

The hydrolysis reactions of aluminum provide the main buffering mechanism in the pH range of 3.5 to 5.5 in mineral soils. Solid phase aluminum occurs in soil mineral structures, in interlayers of expansible clay minerals, and in poorly ordered minerals such as allophane and oxyhydroxides. With reduction in soil pH, hydronium ions are adsorbed on colloidal surfaces producing positively charged sites. Eventually, mononuclear aluminum ions are produced and these occupy permanent exchange sites replacing base cations. The exchangeable hydroxy-Al ions and hydroxy-Al surfaces provide buffering such that the soil pH is usually maintained above a value of 4. In this pH range, Ulrich (1980) indicates that aluminum buffering occurs as follows:

$$AlOOH \cdot H_2O + xH^+ = Al(OH)^{x+}_{3-x} + xH_2O \qquad [16]$$

The buffering capacity is such that a soil with 1% clay is equivalent to about 100-150 kmol H^+ ha^{-1} dm^{-1}. In this buffering range, leaching of Al and Mn can occur, but the soil fabric is stable (Ulrich 1980).

At soil pH less than 3-3.5, iron buffering occurs as follows:

$$Fe(OH)_3 + xH^+ = Fe(OH)^{x+}_{3-x} + xH_2O \qquad [17]$$

Under such extremely acid conditions, growth on mineral soil is inhibited (Ulrich 1980).

Aluminum interlayers and silanol (-SiOH) groups of silicate lattice structures may account for buffering at soil pH values greater than 5.5 (Thomas and Hargrove 1984).

In the pH range 5-6.5, Ulrich (1980) indicates that buffering capacity of a soil with 1% clay is equivalent to about 6 kmol H^+ ha^{-1} dm^{-1}. In this range, the salt concentration in solution is low, Ca leaching occurs and the soil fabric is relatively unstable.

In the pH range of 6.5-8.3, buffering by carbonates occurs as follows (Ulrich 1980):

$$CaCO_3 + H_2CO_3 = Ca^{2+} + 2HCO_3^- \qquad [18]$$

The buffer capacity is such that a soil with 1% $CaCO_3$ is equivalent to about 150 kmol H^+ ha^{-1} dm^{-1}. In this range, the salt concentration of the soil solution is high and Ca leaching occurs, but the soil fabric is stable.

In the normal pH range of soils, organic soil colloids can also act as a buffering system. Carboxylic (-COOH) groups are chiefly responsible for acidity in organic matter between pH values 3 and 7. Phenolic-OH groups contribute acidity between pH 8 and 12. Between pH 7 and 8, overlap of these groups and $x\text{-}NH_2$ groups accounts for acidity (Gessa 1979). The buffering by humus particles can be represented by the following reaction (Bache 1979a):

$$R\text{-}COOH + H_2O = R\text{-}COO^- + H_3O^+, \quad pK = 5.5 \pm 1.7 \qquad [19]$$

The buffering range is assumed to span one pH unit on either side of the pK value, so that organic matter buffering is active over the range of pH values for most soils.

2.1.5 Types of Soil Acidity

2.1.5.1 Introduction. Many approaches have been used to characterize the components of total soil acidity (Bohn et al. 1979). Two generally recognized components are exchangeable and non-exchangeable acidity. These are differentiated mostly on the basis of the experimental method used to measure the particular fraction.

2.1.5.2 Total acidity. Total acidity is defined as the amount of base required to bring the soil to a pre-determined pH value under standardized conditions (Bache 1980a). It is the combined total content of H^+ in the soil plus the undissociated forms of acidity in the soil (Holowaychuk and Lindsay 1982). It is determined by the amount of base (NaOH or $Ca(OH)_2$) that is required to raise the soil pH to a value of 7.0, 8.0, or 8.2. This is accomplished either by reacting the soil with $BaCl_2$ buffered with triethanolamine at pH of 8 or 8.2 (Thomas 1982), or by titrating the soil with a strong base to a preset pH (Bohn et al. 1979); the value of total acidity is usually expressed in cmol(+)kg^{-1}. Soil titration parameters need to be specified for the measurements to be meaningful, as titrations are known to be sensitive to experimental conditions such as time, method of stirring, and period between base additions.

Total acidity is the sum of both exchangeable and non-exchangeable acidity. Other terms have been used to denote total acidity; some still use the term "titratable acidity" while others use "potential acidity" (Thomas 1982).

2.1.5.3 Exchangeable Acidity. Exchangeable acidity is the part of the total acidity that is estimated by leaching or extracting the soil with a concentrated (usually 1 M) unbuffered solution of a neutral salt such as KCl, NaCl, or NH_4Cl, and titrating the extract with base (Bache 1980a).

The acidity extracted in this fraction consists of exchangeable monomeric aluminum and iron, and hydrogen, although the hydrogen has been attributed to Al^{3+} hydrolysis (Thomas and Hargrove 1984). Exchangeable acidity is detected only in soils having pH values lower than 5.5, where most of the acidity is made up of exchangeable aluminum, while exchangeable hydrogen is measurable only when the soil pH is lower than 4 (Bohn et al. 1979).

2.1.5.4 Non-exchangeable Acidity. The balance between total and exchangeable acidity is referred to as non-exchangeable acidity; other terms used to name this fraction include residual, hydrolytic, and titratable but not exchangeable acidity (Bache 1979a, 1980a; Bohn et al. 1979).

Non-exchangeable acidity constitutes the major part of total acidity, and exists in soil mainly in undissociated forms (Bache 1979a).
This acidity arises from the neutralization of hydroxy-Al polymers on soil surfaces,

$$X\text{-}Al(OH)^{2+} + OH^- = X\text{-}Al(OH)_2{}^{2+} + H_2O, \qquad [20]$$

neutralization of hydrogens from organic functional groups,

$$R\text{-}COOH + OH^- = R\text{-}COO^- + H_2O, \qquad [21]$$

and displacement of adsorbed anions producing what Mehlich called "acidity due to anions" (Bohn et al. 1979):

$$X\text{-}Al(OH)(H_2PO_4) + OH^- = X\text{-}Al(OH)_2 + H_2PO_4{}^- \qquad [22]$$

These are mainly found in the pH range of 5.5 to 7.0, and can be present even at pH values higher than 7 (Bohn et al. 1979):

2.1.6 Cation Exchange and Soil Acidity

2.1.6.1 Cation Exchange. The negative charges found on the colloidal clay and humus fractions of the soil matrix give rise to the phenomenon of cation exchange. The cation exchange capacity of a soil is made up of a constant, permanent charge and a variable pH-dependent charge (Bache 1979b).

The permanent charge arises from the isomorphic substitution of Al^{3+} for Si^{4+} in the tetrahedral layers, and of Mg^{2+} or Fe^{2+} for Al^{3+} in the octahedral layers of clay-size layer silicates (Bache 1979b). The result of such substitution is that some of the O^{2-} and OH^- charges in the clays are left unbalanced, and the clay lattice acquires a net negative charge. Isomorphic substitution occurs mainly during the crystallization of layer silicate minerals, and is the principal source of negative charge for the 2:1 and

2:1:1 type layer silicates, but is of minor importance for the 1:1 type minerals (Bohn et al. 1979). The permanent charge is independent of soil pH and is generally constant for the pH range of most soils.

The source of the variable charge in soils is the pH-dependent dissociation of functional groups on the surfaces of soil solids. These functional groups include the hydroxyl (-OH), carboxyl (-COOH), phenolic ($-C_6H_4OH$), and amine ($-NH_2$) groups of soil humus, and the aluminol ($-Al(OH_2)^+$) and silanol (-SiOH) groups on the crystal edges of layer silicates and the surfaces of aluminosilicate gels (Bohn et al. 1979). Another source of variable charge is the "blocking" of negative charges by adsorbed hydroxy aluminum cations (Bache 1979b). In surface soils, most of the variable charge is contributed by the soil humus fraction, whose negative charge increases with pH from almost nothing at pH 3 to about 200 $cmol(+)kg^{-1}$ at pH 8 (Thomas and Hargrove 1984). For the layer silicates, it is estimated that 5-10% of the total negative charge of the 2:1 type is pH-dependent, while 50% or more of the negative charge of the 1:1 type is pH-dependent (Bohn et al. 1979).

2.1.6.2 Base Saturation. Base saturation is defined as the ratio of "basic" exchangeable cations to the total cation exchange capacity (CEC) of the soil. These base cations include Ca, Mg, Na, K, and NH_4, and the degree of base saturation (BS) is:

$$BS = [(Ca + Mg + Na + K + NH_4)/CEC]100 \qquad [23]$$

The degree of base saturation is dependent on the pH at which the CEC measurement was made; as the CEC increases with pH, the BS value decreases with pH.

In the measurements of CEC, the soil is leached with various salts to extract the exchangeable cations and to saturate the exchange complex with an index cation; after saturation, the index cation is leached and CEC is calculated from the total content of the index cation in the leachate. The CEC and exchangeable cations are measured by one or more of the following three methods performed at three different pH values (Thomas and Hargrove 1984):

1. at the soil pH by using an unbuffered salt solution (KCl, NaCl, or NH_4Cl), where the CEC is sometimes referred to as the "effective CEC" of the soil;
2. at a neutral pH by leaching with a buffered ammonium acetate solution at pH 7; this pH is chosen as it represents soil pH containing $CaCO_3$ in equilibrium with CO_2 at a partial pressure higher than atmospheric and more representative of CO_2 pressures in the soil matrix; and
3. at pH of 8.2 by leaching with a solution of $BaCl_2$ buffered with triethanolamine; this pH value corresponds to the equilibrium pH of a soil containing $CaCO_3$ in equilibrium with atmospheric CO_2.

The three methods give the same results for exchangeable base cations, but different values for CEC and exchangeable Al and H (Thomas and Hargrove 1984). Method 3 gives the highest values for CEC and thus the lowest BS values, method 1 shows the lowest CEC and highest BS values, while method 2 gives values intermediate between the other two. The increase in CEC from methods 1 to 2 is attributed to the increase in exchangeable and non-exchangeable "hydrolytic" acidity that are both pH-dependent. Bache (1979b) presented the relationship between CEC and exchangeable ions as follows:

$$\text{CEC} = \begin{array}{c}\text{exchangeable}\\ \text{base cations}\end{array} + \begin{array}{c}\text{exchange acidity}\\ \text{(acid cations)}\end{array} + \begin{array}{c}\text{hydrolytic}\\ \text{acidity}\end{array} \qquad [24]$$

It can be seen that as the pH of the extracting solution increases to 8.2, the amount of exchangeable base cations stays constant, but the CEC increases due to the increase in acidity concurrent with the solution pH increase; the result is that BS is decreased as the pH of solution is increased.

The strong dependence of BS on the pH of the solution used to extract exchangeable cations and measure CEC makes BS an unreliable measure of soil saturation with base cations or unsaturation with acid cations. A realistic picture of any losses in BS due to acidification is best attained at the native soil pH, while the use of other methods is more appropriate for comparison purposes as required, for example, in soil surveys.

2.2 ACIDIFICATION OF SOILS

2.2.1 Acidification in Soil Genesis

Soils are considered to be a function of a number of individual, but interdependent factors, namely parent material, climate, biota, topography, and time (Jenny 1941). Different degrees of expression of these factors lead to formation of many different kinds of soil. Parent material, topography and time are sometimes referred to as the passive factors of soil formation. Climate and biota are considered to be active factors which drive soil processes. Processes that occur in the formation of soils are additions, losses, translocations, and transformations (Simonson 1959).

Acidity in soil, and the relative effect of acid deposition on soil, is more readily understood in terms of the above framework of factors and processes in soil formation. By definition, acidification is an increase in the total acidity of the soil and a reduction in its pH. Thus, over time, there is a transformation of soil chemical conditions with respect to H. Climate influences the acidification of soils through the effect of temperature and water on weathering and on the types and activities of soil biota. Acid inputs result in reaction with and removal of $CaCO_3$. Hydrolysis, hydration, and carbonation are some acidifying processes which decompose soil mineral constituents (Tabatabai 1985). The overall effect is that soils become more acidic as rainfall increases or as duration of these various processes increases.

Biota have a significant influence on soil acidity with different flora and fauna influencing soils in different ways. The large differences between grassland and forest soils provide an example relevant to Alberta. Decomposition of vegetative matter in the surface soil layers results in release of bases and a variety of compounds, including inorganic and organic acids. Biological activity, nutrient cycling and production of acids is especially high in the surface organic layer of forest soils. Over time, the pH of these soils is significantly reduced. Grassland soils are generally less acidic than forest soils because, being drier ecosystems, leaching is less intensive, and because grasses more effectively recycle nutrient elements, especially the cations Ca, Mg, K and Na.

The processes which directly or indirectly lead to acidification of soils are more thoroughly discussed in the following sections. Soil forming factors and processes important in the development of Alberta soils are discussed in Section 4.

2.2.2 Sources of Soil Acidity

2.2.2.1 Introduction. There are various sources of hydronium ions that are responsible for soil acidity. Krug and Frink (1983a) have described the various sources, sinks, and pathways of soil acidity diagrammatically as depicted in Figure 1. Some of the more important sources are discussed in the following sections.

2.2.2.2 Atmospheric and Soil Carbon Dioxide. Deposition of acid by rainfall is a natural phenomenon resulting from the chemical equilibrium between atmospheric moisture and CO_2. The natural acidity of precipitation is controlled by the CO_2 - HCO_3^- equilibrium. The concentration of CO_2 in the atmosphere is 316 mg kg^{-1} (or 0.03% by volume, or a partial pressure of 3.16×10^{-4} atm). Carbon dioxide when dissolved in water forms carbonic acid with a consequent production of H^+:

$$CO_2 + H_2O = H_2CO_3 = H^+ + HCO_3^- \qquad [25]$$

Atmospheric water in equilibrium with CO_2 in the air would have a pH of 5.65 (Reuss 1975; Bache 1980a). A rainfall of 50 cm would generate 0.0125 kmol ha^{-1} of H^+. In comparison, water in soils having 1% of CO_2 in the soil air would have a pH of 4.9 (Bache 1980a), while water in soil having 10% CO_2 would have a pH of 4.45 (Tabatabai 1985). A pH of about 5 is thus quite common in subsurface soils where H_2CO_3 is the only source of acidity. Acidity generated in topsoil can amount to 1 kmol ha^{-1} y^{-1} of H^+. This acidity-generating property of CO_2 is less effective in more acid soil environments since it is released from solution; that is, the H^+ is in excess and drives the equation in the opposite direction. The acidity generated in this manner is relatively weak, but a continuous supply of CO_2 results in generation of a significant quantity of H^+ which can dissolve carbonates and hydrolyze silicate minerals.

2.2.2.3 Organic Matter. Soil organic matter consists of live organisms and their undecomposed, partly decomposed, and completely transformed remains. Generally, soil organic matter is the term used to refer more specifically to the non-living material which is a heterogeneous mixture of products resulting from microbiological and chemical transformations of organic remains. Materials recognizable as plant components are termed "plant debris". Substances in which cellular organization of plant material is no longer present are referred to as "humus". Humus includes humic substances which are differentiated on the basis of pH dependent solubility into humic, fulvic and humic fractions, and non-humic substances which are compounds belonging to recognizable classes such as carbohydrates, proteins, lipids, and organic acids (Paul 1970; Oades and Ladd 1977).

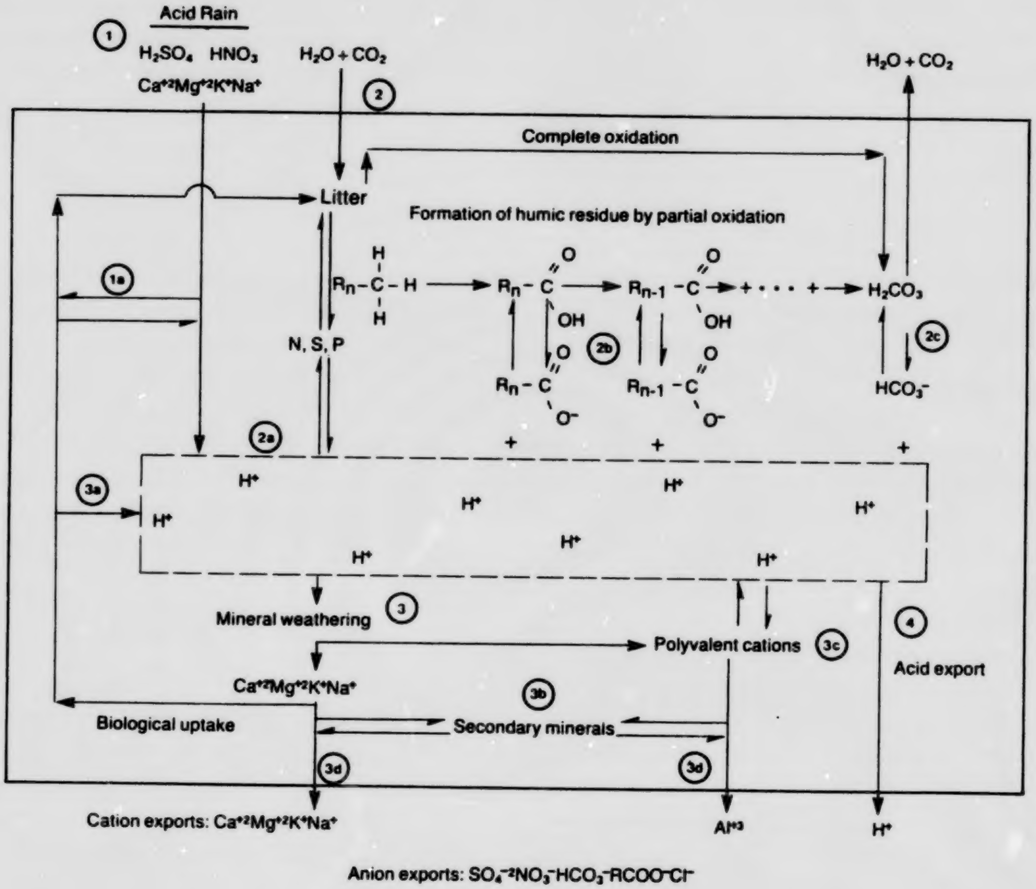
Acid Rain
1
H_2SO_4 HNO_3
$Ca^{+2}Mg^{+2}K^{+}Na^{+}$
$H_2O + CO_2$
2
$H_2O + CO_2$
Complete oxidation
Litter
Formation of humic residue by partial oxidation
1a
R_n-CH_3
R_n-COOH
$R_{n-1}-COOH$
H_2CO_3
N, S, P
R_n-COO^-
2b
$R_{n-1}-COO^-$
2c
HCO_3^-
2a
+
3a
H^+
Mineral weathering
3
Polyvalent cations
3c
4
Acid export
$Ca^{+2}Mg^{+2}K^{+}Na^{+}$
3b
Biological uptake
Secondary minerals
3d
3d
Cation exports: $Ca^{+2}Mg^{+2}K^{+}Na^{+}$
Al^{+3}
H^+
Anion exports: $SO_4^{-2}NO_3^{-}HCO_3^{-}RCOO^{-}Cl^{-}$

Figure 1. Major sources and sinks of acidity in soil (Source: Krug and Frink 1983a).

Acid rain (1) is a source of acidity, and its composition may be altered before reaching the soil (1a). Although biological processes (2) are net sources of acidity, this obscures the fact that they serve as a substantial sink in acid soils through production of weak organic acids (2b) with ultimate conversion to CO_2 and H_2O (2c). Mineral acids (2a) can be cycled rather tightly with some S and N lost to the atmosphere by microbial activity, and some S and P can be converted to essentially insoluble secondary minerals. Weathering of minerals (3) generally consumes acid in excess of cation export (3d), as secondary minerals (3b) and hydrolysis products of aluminum, iron, manganese (3c) accumulate in soil. Aggrading vegetation causes net cation uptake (3a), and contributes to acidification. Rain less acidic than the soil solution promotes acidification by hydrolysis (3c). The electrical charges exported by cations (3d) and acids (4) are balanced principally by anions shown at the bottom of the figure.

In neutral and alkaline soils, most of the organic matter is in the humus form with large proportions in humic and humin fractions. These substances are amorphous, colloidal and dark-coloured polymers, and they have high contents of carboxyl, phenol hydroxyl, and other functional groups that dissociate to produce H^+. These humic materials attack and degrade soil minerals by complexing and dissolving metals. However, Ca^{2+} is selectively adsorbed by humus material and the Ca-humic complexes may counteract acidifying influences (Wiklander 1979). In acid soils, humic and fulvic acids do not appear to have many free -COOH groups but are present largely as Fe and Al complexes (Thomas and Hargrove 1984). With gradual decomposition of organic matter, Al and Fe are released and can contribute to acidity by hydrolysis. However, most acid produced in acid soils is not translocated by runoff nor does it participate in mineral weathering, but upon decomposition is lost from the system as H_2O and CO_2.

Of the non-humic components of organic matter, organic acids can have a considerable acidifying influence on soils. Together with fulvic acids, these materials are produced in considerable amounts where substantial portions of organic matter are in plant debris. Coniferous forests produce very acidic litter and an acidic humus layer. The soluble organic acids and fulvic acids are leached and cause strong acidification and weathering leading to formation of podzols with low base saturation (Wiklander 1979). Podzol A horizons are developed by leaching while illuvial B horizons result from accumulation of Fe, Al, and humic materials. Bases do not moderate the acidifying influence to a great extent because they are mainly kept in the humus layer and in the biological cycle.

The litter from hardwood deciduous trees is generally somewhat less acidic and higher in base content than that of conifers. Therefore, in mixed forests, hardwood litter tends to increase the base content, improve the buffering capacity and reduce acidifying influences. Grasses are generally more effective than deciduous trees in reducing acidification because they contain higher contents of base cations and because they are more effective than trees at offsetting leaching by recycling nutrient elements (Tabatabai 1985).

2.2.2.4 Oxidation of Ammonia and Reduced Sulphur. Ammonium ions are produced in soil as a result of microbial decomposition and mineralization of plant residues and humus. Ammonium based fertilizer application can be another major source. The ammonium ions are microbially oxidized in soil to nitric acid as follows:

$$NH_4^+ + 2O_2 = H_2O + NO_3^- + 2H^+ \qquad [26]$$

The theoretical amount of acid resulting from nitrification of 1 kmol NH_4^+ is 2 kmol H^+ (Bache 1980a; Holowaychuk and Lindsay 1982). The latter would require 286 kg Ca or 714 kg of lime ($CaCO_3$) to neutralize it. However, direct uptake of NH_4^+ by plants, volatilization, denitrification, and a low ratio of excess base to N taken up by plants reduce the net quantity of acidity theoretically produced. Soil acidification due to fertilization with emphasis on Alberta soils is more thoroughly discussed in Section 3.10.1. In summary, there are both natural and anthropogenic sources of NH_4^+ within soils. There may also be atmospherically deposited NH_4^+ of natural or anthropogenic origin.

Acidity is also generated by oxidation of indigenous or added sulphur compounds such as S, FeS, FeS_2, and H_2S. Although sulphur is taken up by plants in the sulphate (SO_4^{2-}) form, it is subsequently converted to reduced states when incorporated into the organic compounds of plant material and soil organic matter. The oxidation of organic sulphur then generates acidity, but there is no net change in acidity as sulphur goes through this cycle (Holowaychuk and Lindsay 1982).

In anaerobic soil conditions sulphate is reduced to sulphide to produce H_2S or FeS_2 (pyrite). Pyrite may also be found in sediments such as estuarine muds and in argillaceous marine deposits such as some of the shales in Alberta. The latter may occur in spoil piles of surface mining operations. Upon exposure to aerobic conditions, these compounds produce acidity by oxidation as follows:

$$FeS_2 + 15/4\ O_2 + 7/2\ H_2O = Fe(OH)_3 + 2SO_4^{2-} + 4H^+ \qquad [27]$$

Highly acidic soils can be formed through these processes; pH values as low as 2 have been reported for floodplain soils containing pyrite (Thomas and Hargrove 1984). The development of anaerobic conditions in soils, during periods of waterlogging as an example, will reverse the reaction above and thereby counteract acidification (Wiklander 1979).

2.2.2.5 Nutrient Uptake by Plants. Acidic substances on root surfaces adsorb cation nutrients from the soil solution and desorb H^+ that replaces base cations from the soil particles:

$$\text{Root-H} + \text{Soil-Me} = \text{Root-Me} + \text{Soil-H} \qquad [28]$$

In cultivated soils and other fertile soils this reaction is likely to exert a depressive effect on the base saturation although it is difficult to quantify (Wiklander 1979).

Ulrich (1980) found that the form in which nitrogen was taken up in a beech forest was a determining factor in the production of acidity. Where N was taken up as NO_3^-, the production of acidity was zero, but it amounted to 4 $kmol(H^+)\ ha^{-1}\ y^{-1}$ if the N was taken up as NH_4^+.

2.2.2.6 Summary. Soil acidification is a natural process in which H^+ production in soils exceeds consumption over time. The mechanisms and intensity of acidification are dependent on the soil forming factors. Table 1, adapted from van Breemen et al. (1983, 1984), summarizes the H^+ productive and consumptive processes in soils.

2.2.3 Leaching and Weathering

Leaching in soil is the downward movement of substances dissolved in percolating waters. Substances such as soluble salts, bases, silicon, and various forms of organic matter in soils are subject to leaching. Leaching mechanisms are complex and involve many variables such as: (1) nature of the soil medium, (2) activities of microorganisms, (3) formation of complex ions, (4) surface charge and exchange properties of soil

Table 1. Summary of proton producing and consuming processes.[1]

Proton-producing processes	Example	Proton-consuming processes
(1) Atmospheric input	H^+ (aq(rain/drain water)) = H^+ (aq(soil solution))	(1) Drainage
(2) Assimilation of cations	$M^+ + R_{OH} = R_{OM} + H^+$ M^+ + H.Ligand = M.Ligand + H^+ NH_4^+ + R.OH = R.NH_2 + H_2O + H^+	(2) Mineralization of cations
(3) Mineralization of anions	R.H_2PO_4 + H_2O = R.OH + $H_2PO_4^-$ + H^+ R.SO_4 + $2H_2O$ = R.$(OH)_2$ + SO_4^{2-} + $2H^+$ R.NO_3 + H_2O = R.OH + NO_3^- + H^+ R.NH_2 + $2O_2$ = R.OH + NO_3^- + H^+ R.SH + 3/2 H_2O + 7/4 O_2 = R.OH + SO_4^{2-} + $2H^+$	(3) Assimilation of anions
(4) Dissociation of acids	$H_2O = OH^- + H^+$ $CO_2 + H_2O = HCO_3^- + H^+$ R.OH = R.O^- + H^+ H_n.Anion (aq) = Anion^{n-} (aq) + nH^+	(4) Protonation of anions
(5) Oxidations	$H_2S + 2O_2 = SO_4^{2-} + 2H^+$ SO_2 + 1/2 O_2 + H_2O = SO_4^{2-} + $2H^+$ $NH_4^+ + 2O_2 = NO_3^- + H_2O + 2H^+$ NOx + 1/4 (5-2x)O_2 + 1/2 H_2O = NO_3^- + H^+ N_2 + 5/2 O_2 + H_2O = $2NO_3^-$ + $2H^+$ Fe^{2+} + 1/4 O_2 + 5/2 H_2O = $Fe(OH)_3$ + $2H^+$ FeS + 9/2 O_2 + 5/2 H_2O = $Fe(OH)_3$ + SO_4^{2-} + $2H^+$ FeS_2 + 15/4 O_2 + 7/2 H_2O = $Fe(OH)_3$ + $2SO_4^{2-}$ + $4H^+$	(5) Reductions
(6) Reverse weathering of cations	M^{n+} (aq) + 1/2nH_2O = 1/2nM_2/nO(s) + nH^+ (aq)	(6) Weathering of metal oxide components
(7) Weathering of anionic components	$^*NO_{(m+n)}(S) + mH_2O = NO_{(2m+n)}^{2m-} + 2mH^+(aq)$ $Ca(H_2PO_4)_2 = CaHPO_4 + H_2PO_4^- + H^+$	(7) Reverse weathering of anions
(8) Cation/hydronium exchange	M^{n+} + nH.Exch = M.Exch + nH^+	(8) Hydronium/cation exchange
(9) Anion exchange (desorption)	SO_4. Exch + $2H_2O$ = Exch.$(OH)_2$ + SO_4^{2-} + $2H^+$	(9) Anion adsorption

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[1] Adapted from the original tables in van Breeman et al. (1983, 1984)

particles, (5) partial pressure of CO_2, and (6) porosity and hydraulic conductivity of the soil (Finkl 1979). The degree and kind of leaching differs under acid, neutral, and alkaline conditions, and under oxidizing versus reducing conditions.

Substances such as salts which readily dissolve in water are transported by percolating water to lower horizons or out of the soil profile. Other substances such as alkali and alkaline earth elements in minerals and in exchangeable form are mobilized by hydrolysis due to dilute acids such as carbonic acid formed when CO_2 is dissolved in water (equation 25). The kind and extent of soil exchangeable base mobilization is governed by exchange reactions with cations in the percolating water (Holowaychuk and Lindsay 1982). The relative bonding energy of cations on exchange sites and of those in soil solution influences the extent to which different cations are displaced or adsorbed. For example, Na^+ is easily displaced by Ca^{2+} because of the much higher bonding energy of the latter. At a pH of 5.5 or higher, hydrogen ions have high binding energy and are very efficient in displacing exchangeable bases.

Weathering of soil minerals can be relatively higher with higher leaching rates. In addition to mobilization of alkali and alkaline earth elements during hydrolysis, silicon can also be released and leached, mainly in the form of silicic acid. Because leaching reduces the concentration of soluble weathering products, conditions conducive to continuation of weathering are produced. These processes not only contribute to loss of bases but in the case of primary aluminosilicate minerals, increase the aluminum content of the weathering residues (Holowaychuk and Lindsay 1982). Aluminum and iron form complexes and chelates with acid radicals or functional groups of humic materials. In these forms, iron and aluminum are subject to leaching, but not to as large a degree as the alkali and alkaline earth elements or silicon. The net result of these processes is that bases are depleted from soils and acidity is increased due to higher proportions of hydronium ions and aluminum and to an accompanying decrease in base saturation of the exchange complex.

As noted above, the effects of leaching differ under different soil conditions. In acidic soils, the soil solution tends to be enriched with carbon dioxide and humic materials. The alkali and alkaline earth elements are readily leached, while humus and silicon are leached to a lesser extent. Iron and aluminum, however, are removed in small amounts. In neutral soils, the alkali and alkaline earth elements are also leached, but tend to be deposited in deeper horizons as carbonates and sulphates. Leaching of aluminum, iron, humus, and silicon is negligible. In alkaline soils, leaching is restricted because these mainly occur in arid regions. The effects of leaching on acidification are thus greatest in those soils which are already acidic, and it would appear that any additional acidic inputs would accelerate soil acidification and leaching of base ions.

3. INFLUENCES OF SOIL ACIDITY AND ACIDIFICATION ON OTHER PROPERTIES

3.1 ORGANIC MATTER

Organic matter was described in Section 2.2.2.3 as consisting of relatively undecomposed (plant debris) and decomposed (humus) components. Furthermore, the humus component consists of humic (humic, fulvic, and humin fractions) and non-humic substances. The physical and chemical forms of organic matter differ among soils. A number of major kinds of organic horizons in soils are widely recognized (Buol et al. 1980). For purposes of discussion in this report, the following forms are recognized:

1. organic matter of Chernozemic soils and surface layers of cultivated soils; along with the melanic organo-mineral horizons of deciduous forest soils, this type is commonly referred to as "mull";
2. the L-F-H layers, in different combinations, of forest soils; this type is equivalent to "mor" as described by Buol et al. (1980);
3. organic matter of Solonetzic B horizons, which occurs as dark coatings on the surfaces of peds;
4. organic matter of Podzolic B horizons occurring as dark reddish brown to black, soft, weakly granular layers; these are relatively uncommon in Alberta; and
5. organic matter of Organic soils, or peat, which can occur in various degrees of decomposition.

The organic fraction of soils accounts for the major portion of pH dependent CEC (Bache 1976), and from 25 to 90% of the total CEC of the surface horizons of mineral soils (Stevenson 1982).

The cation exchange capacity is influenced by pH, and the negative charges associated with humus colloids are dependent on pH. The covalent-bonded hydrogens of carboxyl (-COOH) and phenol (R-OH) groups are not dissociated at low pH values. Hydrogen dissociation occurs with increasing pH, and negative charges on the colloids develop.

Holowaychuk and Lindsay (1982) indicated the manner in which inorganic and organic soil materials differed in the relative extent of total negative charge exhibited on a weight basis. From Figure 2, it can be seen that the CEC of organic matter is much more strongly influenced by soil pH than is the CEC of clay. Humus can make a significant contribution to the total CEC of the soil even though the amounts present may be quite low relative to clay. Many of the exchange sites of organic matter in mineral soils may be blocked due to formation of organo-clay and organo-metal complexes. Upon liming a soil, the CEC may increase due to disruption of the organo-mineral complexes and to dissociation of carboxyl and phenol groups (Stevenson 1982). The acidification of soil would have the effect of reducing effective CEC and displacing base cations which may then be removed from the system by leaching.

Soil acidity affects the rate of organic matter decomposition. Jenkinson (1981) demonstrated that ryegrass residue decomposed at similar rates in soils of pH 6.9 and 4.8, but the rate was somewhat diminished at pH 3.7. This reduction at low pH was attributed to the restriction of activities of the soil microbial population to a

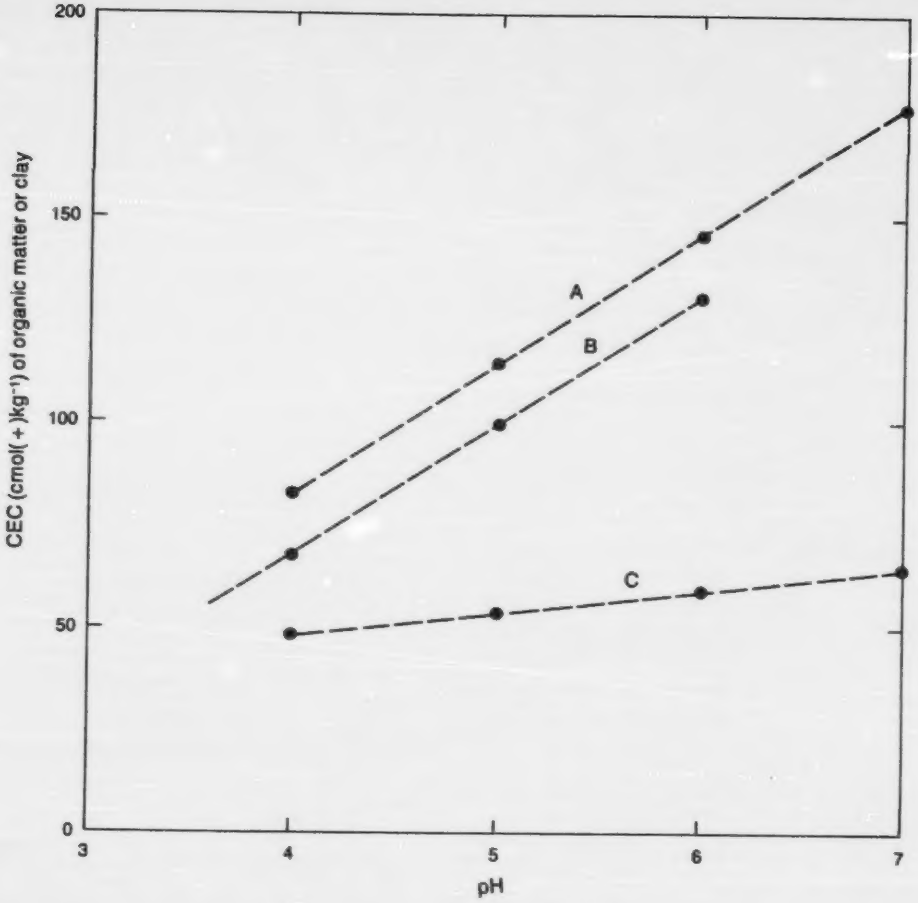


Figure 2. Reduction in cation exchange capacity of organic matter and clay with decrease in soil pH.

A - Organic matter fraction in Ap horizons (Helling et al. 1964)
B - Humus of forest soils (Kalisz and Stone 1980)
C - Clay fraction in Ap horizons (Helling et al. 1964)

relatively small number of species. The decomposition of forest litter has been shown to be pH dependent, but at the normal range of soil pH, the effect is not large. This is possibly due to the acid tolerance of decomposing fungi (Abrahamsen et al. 1980). Among hypothetical impacts of acidification related to organic matter in soils, the following have been listed by McFee (1982): decreased rate of C mineralization as a result of acidification or associated trace metal toxicity; shift from bacteria to more tolerant fungi; decreased ammonification and nitrification; and trace metal toxicity. Most of these influences of acidification are the subject of other reviews and only chemical and physical-morphological aspects of these influences are reviewed here.

Increased acidification due to fertilization has been shown to have an influence on humus forms and morphology in hayfields (Barratt 1970). Hayfields treated with ammonium sulphate developed extremely acid soil conditions (pH 4.5-3.9), formed a mor type of organic matter, and showed reduction in decomposition rates and in earthworm activity. Use of other fertilizers and topdressings did not produce conditions which were as acidic and mull types of morphology were maintained. The impacts of these topdressing effects on productivity were not addressed by Barratt (1970), but a change to less productive and less nutritious species composition of the haycrop in acidified plots was indicated. Some evidence has been found from the Breton Plots in Alberta and from the Rothamsted Experimental Station that addition of appropriate commercial fertilizers increases organic matter content of tilled soils (Robertson 1983). The increases are slight, probably due to removal of portions of crops, and there is little information available on effects when all residues are returned to the soil and on effects specifically in relation to acidification by fertilizers or other sources.

In a review of the effect of low pH on the chemical structure and reactions of humic substances, Schnitzer (1980) indicated that fulvic acids could be dissolved and mobilized under conditions of moderate acidity while humic acid particles tend to become aggregated. Humic acids are thought to exist in solution as randomly coiled polymers which are more tightly coiled and cross-linked in the centre (Stevenson 1982). When humic polymers are saturated with protons or polyvalent cations, or dispersed in high electrolyte solutions, they shrink due to association of ionizable groups and cross-linking of polymers by interaction of functional groups and polyvalent cations. In acid soils, Al^{3+} is most important while Ca^{2+} is most important in neutral and alkaline soils. This cross-linking results in smaller, denser, and more rigid particles which should be more stable to both chemical and biological attack. However, the configuration of humic substances in soils is not known. They are concentrated at specific sites and do not seem to be spread uniformly through the soil (Oades 1986). The implication is that, all other things being equal, the acidification of soil would tend to reduce the rate of decomposition. In assessing this acidification effect, however, one would need to consider the stimulating effect on decomposition resulting from addition of major nutrients such as N and S which may accompany acid inputs.

In soils where fulvic acids are the major organic components, such as Podzolic soils, losses of organic matter resulting from acidification can be substantial (Schnitzer 1980). Adsorption of fulvic acids on mineral surfaces may occur between pH 2 and 3. Acid conditions may also increase the interlayer adsorption of fulvic acids by expanding clay minerals. Both the increased acidity and solubilized fulvic materials can accelerate weathering of minerals with a net result of less favourable conditions for biological activity and reduction in soil fertility (Schnitzer 1980). Most of the effects, however, occur at extremes of acidity which do not occur in soils except in some unique situations.

Organic matter and mineral materials in soils exist in various forms and degrees of association with each other. The mechanisms by which they interact and the kinds of products they form in different soil environments has been reviewed in a number of publications (Schnitzer 1978; Burchill et al. 1981; and Stevenson 1982). The role of organic matter and its interactions with soil mineral constituents in aggregation of soils has been reviewed by Tisdall and Oades (1982) and Oades (1984). The effects of acidification on organo-mineral associations accompany other processes such as base cation loss and increased weathering, as discussed in other sections. The discussion in this section deals mainly with implications regarding soil colloid properties and structure.

Negatively charged organic molecules promote the dispersion of clays in at least two ways: (1) organic anions complex trivalent and divalent metal ions, thus reducing their concentration in solution, and they react with positive sites associated with trivalent metals on clay and oxide surfaces; and (2) sorbed organic anions increase the negative charge on colloid surfaces, thus increasing the diffuse layer of cations associated with the surfaces (Oades 1984). An effect of increased soil acidity discussed above is that fulvic acids can become dissolved and mobilized. A secondary effect could be an increased tendency for colloids to disperse and become translocated, thus accelerating podzolization and lessivage. The induced dispersion may worsen already unfavourable conditions in certain tilled soils which tend to develop surface crusts and "hard setting" properties. These processes can occur in soils with pH of about 6, with no free $CaCO_3$, and with little or minor solubilized Al (Oades 1984). Such conditions exist in many of the tilled Luvisolic soils of western and central Alberta.

Clays and organic materials are polyanions which can be bridged by polyvalent cations such as Ca, Mg, Al, and Fe, and others which occur in minor amounts such as Mn, Zn, and Cu. While divalent ions may exist as single ions with double charge which align water dipoles, Al and Fe are more likely to exist as polycations resulting from hydrolysis and polymerization (Oades 1984). The cation bridges can be disrupted by treatment of soil with complexing agents and acids, and soil aggregates thus become destabilized (Hamblin and Greenland 1977).

Goh et al. (1986) recently reported on the physico-chemical effects of long-term use of urea and ammonium based fertilizers on a Black Chernozemic soil in Alberta. The main effects were lowered pH and altered balance among Al and basic cations, exchangeable acidity, and titratable acidity. Organic matter content increased with fertilizer usage, but there was evidence from microscopic examination of thin sections that soil microstructure had deteriorated.

Liming of soil would have an opposite effect in that added Ca would produce clay-humus interactions via the cation-bridge mechanism. Liming has been shown to improve the structural stability and tilth of tilled Luvisols in northeastern Alberta (Hoyt et al. 1981). Thus, in addition to the acid neutralizing capacity provided by $CaCO_3$, deleterious structural effects of acidification can also be reversed by liming.

3.2 SOIL CATIONS AND LEACHING

Effects of acidification on the soil exchange complex have been summarized by McFee (1982), Mortvedt (1982) and Tabatabai (1985) as follows:

1. decrease in CEC as a result of clay alumination;
2. increase in the CEC of Ultisols as a result of sulphate adsorption;
3. decrease in base saturation and increase in soil acidity; and
4. increased formation of hydroxy - Al interlayers under acid weathering.

None of these effects resulting from acid deposition has been convincingly demonstrated especially in agricultural soils. Ulrich et al. (1980), in a study of a soil under beech forest in Germany, related reduction in soil pH to wet and dry inputs of acidity which amounted to about 1 kmol ha^{-1} y^{-1}. A reduction in CEC was ascribed to an increase in exchangeable Al. This was accompanied by increased levels of Al in soil solution, as well as by increases in exchangeable H and Fe. The soil was already strongly acid (pH 3 to 4) so that any increased acidity would solubilize Al in the form of Al or Al hydroxy cations. The Al polycations are adsorbed, even in preference to H^+, by the permanent negative charges on clay minerals (Bohn et al. 1979). The adsorbed Al will be in equilibrium with Al^{3+} in solution and contribute to soil acidity through hydrolysis.

Various studies on soil acidification caused by use of nitrogenous fertilizers have been carried out. The following effects on exchange properties were noted by Ross et al. (1985) in fertilized apple orchard soils in the Okanagan Valley of British Columbia: reduction in pH; reduction in permanent charge CEC; reduction of base saturation percentage; and reduction of ratios of exchangeable Ca/Mg, Ca/K, and Mg/K. These results suggested that concerns about Ca and Mg nutrition of fruit trees, and possible Al and Mn toxicity, were warranted. However, it was suggested that any adverse effects could be reversed by appropriate changes in management practices, including lime application.

Acidification to pH values lower than about 3.5 is not likely under natural conditions due to the strong buffering of Al hydrous oxides in the pH range 3 - 5 and to replenishment of cations by mineral weathering. Mobilization of Al in soils has been demonstrated in lysimeter experiments in which soils were exposed to artificial acid rain (Abrahamsen et al. 1976) and leaching of Al to watersheds from forest soils exposed to acid precipitation was shown by Cronan and Schofield (1979) and others. Krug and Frink (1983a) have reviewed the factors which govern Al dissolution and mobility and suggest that other cations, anions, and other substances must be considered. Krug and Frink (1983a,b) and Nilsson and Bergkvist (1983) noted that high concentrations of Al in soil solution and shallow groundwater may be a natural phenomenan related to climatic factors.

Calcium and magnesium exist in the soil predominantly in the form of carbonate minerals (mainly calcite and dolomite), in the soil exchange complex, in silicate minerals and in organic and organo-mineral complex forms. Increased acidification would have the effect of releasing cations to the soil solutions due to:

1. accelerated solubilization of carbonates;
2. replacement on the exchange complex with H and Al polycations;
3. weathering of silicate minerals; and
4. disruption of cation bridges in organo-mineral complexes and release of the cation.

The solutes may subsequently be leached to lower parts of the soil profile or to groundwater. The effects regarding exchangeable cations and release by weathering also apply to K and Na, as well as to several micronutrient cations such as Mn, Fe, Zn, and Cu.

The influence of acid deposition on soil cation removal has been the subject of several studies, some of which have been reviewed by Johnson et al. (1983). Studies of Inceptisols, Ultisols, and Spodosols were carried out in Washington, Tennessee, Alaska, and Costa Rica. In none of these studies were base cation losses due to atmospheric inputs considered to be significant. With regard to natural leaching losses, organic acids appear to play a major role in cold region soils undergoing podzolization, carbonic acid may play a major role in tropical and temperate soils, and nitric acid may have an important role in nitrogen rich soils such as those with N-fixing vegetation.

The various influences of acid deposition on cations in soils may best be described by examination of components of models developed to simulate chemical processes in soils. A number of models based on similar concepts have been developed (Christopherson et al. 1982; Gherini et al. 1985); those of Reuss (1980) and Arp (1983) are discussed below. It is not the intention here to discuss the model per se, but to take advantage of the integrative nature of models to summarize the main factors influencing cation processes in soils. These factors, according to Arp (1983), are the following:

1. the cation exchange capacity, and the proportion of pH dependent and pH independent CEC;
2. the number of cation exchange sites in a unit volume of soil;
3. the base saturation percentage of soil;
4. the various soil buffer ranges, buffer capacities and buffer rates, as discussed in previous sections;
5. the dynamics of C, N and S, particularly their influence on production and neutralization of acids and bases;
6. atmospheric inputs of H^+ ions; and
7. reactions of H^+ inputs in the soil.

Specific factors used by Reuss (1980) to predict the distribution of ions between the soil solution and sorbed or exchangeable phases were as follows:

1. the relationships between lime potential and base saturation;
2. the equilibrium between CO_2 partial pressure and H^+ and HCO_3^- in solution;
3. the apparent solubility product of $Al(OH)_3$;
4. the equilibrium of cations and anions in solution;
5. the Langmuir isotherm description of sulphate sorption; and
6. mass balance.

Reuss' (1980) model predicts that for acid inputs to non sulphate sorbing soils there would be almost a 1:1 removal of bases except in soils of very low base saturation. As base saturation is depleted, Ca removal would decrease until Ca input (accompanying the acid deposition) equaled the amount leached. In systems where evapotranspiration exceeds precipitation, the soil solution would become more concentrated and amounts leached would be reduced. In soil systems with high CO_2 partial pressure, Ca leaching increased with increasing lime potential. In sulphate adsorbing soils, the model predicted a dampening effect on cation loss.

Limitations of Reuss' (1980) model are that: (1) only calcium is considered, although other cations could be included; (2) release of cations to the exchange complex by weathering is not considered; and (3) it is strictly abiotic and does not take plant nutrient uptake into account. Nevertheless, it does suggest that acidification and depletion of bases resulting from strong acid deposition could occur within a relatively short time period.

3.3 SOIL ANIONS

Anion sorption properties are important in terms of availability of plant nutrients and regulating leaching rates of some elements. The general order of affinities of soil for major anions is as follows:

$$H_2PO_4^- > SO_4^{2-} > Cl^- = NO_3^- \qquad [29]$$

Phosphate species ($H_3PO_4^-$, $H_2PO_4^-$, HPO_4^{2-}, PO_4^{3-}) and sulphate anions can be specifically bound through ligands of surface groups of hydrous oxides in particular. Chloride and nitrate are non-specifically adsorbed anions; they are retained electrostatically and indifferently at positive sites in the diffuse double layer of colloid surfaces (Mott 1981). Anion sorption on carbonates is significant in calcareous soils. Layer-lattice silicates may sorb anions at exposed sites where $Al(OH).H_2O$ may create positive charge. Other clay minerals such as imogolite and allophone behave somewhat like hydrous oxides. Organic matter may bind anions by incorporation into its structure or by chelation (Mott 1981).

Nitrate and sulphate are of particular interest since these are major anions occurring in acid precipitation. Nitrate, as noted above, is not specifically adsorbed and thus its concentration in soil solution and its adsorption at any one pH is governed by pH-charge relationships; that is, little or no sorption occurs above the zero point of charge and sorption increases with decreasing pH. Research concerning ligand exchange as a mechanism for sulphate sorption has led to contradictory results, although it is well established that SO_4^{2-} is attracted by hydrous oxide surfaces more than NO_3^- or Cl^- (Mott 1981). Sulphate sorption has been demonstrated in H_2SO_4 leaching experiments in which iron podzols showed higher affinity than semi-podzol or brown earth soils. Sorption was shown to be high in Fe and Al oxide rich Inceptisols of Costa Rica, while smaller quantities were sorbed by various Inceptisols, Ultisols, and Spodosols in the United States (Johnson et al. 1983).

Wiklander (1980) demonstrated that anions and soil type directly affect the adsorption of cations in soil. Na, K, Ca, and Mg associated with Cl^- or NO_3^- were bound less readily than when associated with phosphates. Sulphates had an intermediate effect. Polyvalent anions added to soils increase the adsorption and decrease the leaching of cations. Thus, addition of phosphate fertilizer can have the effect of reducing cation loss due to leaching, especially in soils rich in hydrous oxides of Al and Fe.

An increase in soil solution concentration of anions such as SO_4^{2-} and NO_3^- can have an important influence on the cation composition. High sulphate adsorbing soils will not develop greatly increased SO_4^{2-} solution concentrations until equilibrium is reached. Depending on the sulphate sorption capacity, this may not occur for decades (Reuss 1985). An increase in total anion concentrations in solution will increase the cation content to maintain charge balance. In addition, the relative amounts of cations will change such that there will be a higher proportion of Al^{3+} in solution relative to Ca^{2+} and other mono- and divalent cations. Consequently, loss of Ca^{2+} would increase and the proportions of Al^{3+} in solution will be further increased, even though the total cation concentration increases. Thus, in low base saturation soils, increase in anion concentration in soil solution may lead to concerns about Al toxicity to plants and reduced quality of drainage water in watersheds. Soil types affected are those with hydrous oxide accumulations such as Podzolic and some Brunisolic soils.

3.4 AVAILABILITY OF NUTRIENTS AND TOXIC METALS

Soil elements required in relatively large amounts by plants are generally referred to as macronutrients; this group includes the elements N, P, K, S, Mg, and Ca. Micronutrients are elements required in trace amounts and include Mo, Cu, Co, Zn, Mn, Fe, B, and Cl. Exchange and leaching aspects of base cations and dynamics of N, P, and S are discussed in other sections. A few comments regarding the factors affecting availability of these nutrients are made in this section. Reviews of these topics have recently been provided by Mortvedt (1982) and Tabatabai (1985).

The relative availability to plants of nutrients is largely dependent upon pH. Generally, the highest availability of plant nutrients is promoted by a soil pH between 6 and 7. Only some of the micronutrients, namely Mn, Fe, Zn, Cu, and Co, become more available with decreasing pH. Boron is equally available in the range of about 5 to 7.5, and then decreases beyond this range. Ca, Mg, K, N, P, S, and Mo become less available between pH 5 and 6 (Tabatabai 1985) Mortvedt (1982) has reviewed micronutrients in relation to acid deposition and indicated that few problems would be encountered in agricultural systems since crops are generally grown on soils of higher CEC and buffering capacity than those in many forest ecosystems. In addition, cropped soils are generally managed such that residue returns and liming maintain the soil pH at optimum levels for plant availability. He also suggested that research about long term effects must include the effects of acidity on organic matter-metal associations since micronutrient availability is closely associated with organic matter dynamics.

In mor-type organic matter of forest soils, leaching of trace metals such as Mn, Zn, Cd, Ni, V, Cr, Cu, and Pb has been shown to increase with decreasing pH of artificially added water (Tyler 1978). Thus, although availability of micronutrients increases with acidification, losses from the soil system may also be accelerated. Toxicity resulting from mobilization of heavy metals may be another consequence. The deposition of Ni and Cu to highly acidic soils has been implicated in the destruction of vegetation communities near Sudbury, Ontario (Morrison 1984).

The influence of acid deposition on release of polyvalent metals from mineral soils is affected by organic acids and polyphenols produced by organisms. These are important in the mobilization of oxides of aluminum, iron, and managanese from soils and breakdown of these oxides will release the many trace elements adsorbed by them. Aluminum is the most abundant potentially toxic element in soils. Several elements can be toxic to plants, and micronutrients can also be injurious if present in excess amounts.

Acidification of forest soils may also affect nutrient availability through reduced decomposition and release of nutrients from soil organic matter (McLaughlin 1985). Thus, nutrient availability may be an important problem in forest soils and not so much so in agricultural systems provided sound management practices are followed.

A number of general statements about plant nutrients are made above, but it must be realized that nutrient requirements and availability can vary tremendously among crop and forest species. Therefore, impact assessment of acid deposition must be made for specific vegetation and soil types because information from different sources may not be applicable.

3.5 NITROGEN

Nitrogen has a complex cycle in both terrestrial and aquatic ecosystems. The major reservoir of nitrogen is in the atmosphere, consisting of 80% N, and in the organic matter component of soil. The impact of acid deposition on N cycling in agricultural ecosystems has been reviewed by Olson (1982) and the following summary follows his discussion based on different components of the nitrogen cycle (as underlined).

Nitrogen forms may be both inorganic and organic, although most available information is on inorganic (NH_4^+, NO_3^-, NOx) forms. Inorganic N deposition in North America is highly variable in time and location (ranging from 0.5 to 7.5 kg ha^{-1} during 1980 (Tabatabai 1985). However, atmospheric N sources are small compared to inputs from fertilization and mineralization of organic matter. The inputs may be significant, however, in unmanaged ecosystems such as forest and rangeland. There have been reports of short-term growth rate increases resulting from N, and possibly S, inputs with acid precipitation (Abrahamsen 1980; Tamm and Wiklander 1980; and Tveite 1980).

Mineralization of soil organic N to an inorganic form as a result of microbial decomposition can occur under a wide range of soil pH, from strongly acid to strongly alkaline. Thus, acidification of soil is not thought to greatly influence this process (Olson 1982).

Clay mineral fixation of NH_4^+ within the lattice of 2:1 clays precludes short-term availability to plants but this generally occurs at a pH above neutrality (Penney and Henry 1976).

Microbial immobilization of N in relation to acidity will depend on the activity of microorganisms. Bacteria and actinomycetes develop reduced activity below a pH of about 5.5 and immobilization would therefore be expected to decrease (Olson 1982).

Volatilization losses of NH_3 are fostered by high soil pH and drying conditions.

Nitrification, or oxidation of NH_4^+ to NO_2^- and ultimately to NO_3^-, may be the component of the nitrogen cycle most susceptible to acid deposition. Strong acidity is inhibitory to the organisms responsible, mainly Nitrosomonas and Nitrobacter species. In addition, NO_2^- accumulation may result due to the differential acid tolerance of these two groups.

Denitrification, or the microbial reduction of NO_3^- or NO_2^- to gaseous N either as N_2 or an oxide of N, occurs under conditions of moisture saturation. This process is carried out by microorganisms, but is basically a reductive reaction in which H^+ ions are consumed, thus reducing acidity. Firestone et al. (1980) observed an increase in N_2O formation when soil pH was reduced from 6.5 to 4.9 at 10 mg kg^{-1} NO_3^- concentration. In a study of a forest soil of pH 3.5-3.9, Melillo (1981) found that N_2O was the only significant product of denitrification. The concern about N_2O is on a global rather than a local scale; increases of global N_2O in the atmosphere may have an influence on stratospheric ozone concentrations although the effect is not predicted to be significant (Crutzen 1983).

Uptake by plants is influenced by pH, being optimal above a pH of about 5.

Leaching losses of nitrate are influenced by factors of anion sorption and desorption as discussed previously. Thus, an increase in soil solution concentration of anions would have an inhibitory effect on cation leaching. However, as long as there is net downward movement of moisture through the system, substantial losses can occur. Moreover, if soil reaction is depressed to the extent that plant uptake is hindered, the potentially available N can be lost from the system. Leaching losses due to nitrification and application of NO_3^- forms of fertilizers are a major concern with respect to groundwater pollution.

Soil organic matter fixation of N may increase with increased acidity due to reduction in decomposition rates as indicated previously. Various models have been proposed to describe the N cycle, some of which have been reviewed recently by Van Veen et al. (1981), McGill et al. (1981a), and Juma and McGill (1986). There is a need to compare and synthesize the various models prepared (Juma and McGill 1985), but they provide a promising means of examining N cycle response to acidic inputs to soil and their use warrants further investigation.

Information about the influence of acid deposition on N cycle components in forest ecosystems is inconclusive. Morrison (1984), in reviewing atmospheric input of N to forests, concluded that distinct positive effects seem unlikely, but it is also unlikely to have any major detrimental effect. Van Breeman et al. (1982) suggested that excess nitrogen inputs may ultimately result in soil nitrification and consequently in soil acidification as a consequence of internal NO_3^- production by soil microorganisms. In most cases, however, McLaughlin (1985) considered adverse effects of acid rain N inputs on forest growth to be unlikely because of the size and turnover rates of soil nutrient pools. Thus, as with other nutrients, it is apparent that different situations must be considered individually and adequate characterization of sites, mechanisms, and metabolic processes is necessary to evaluate the significance of altered nutrient exchange to the whole soil plant system (McLaughlin 1985).

3.6 SULPHUR

Sulphur cycling in agricultural systems has been reviewed by Olson (1982). Sulphur has many characteristics in common with nitrogen, including its cycling in the biosphere. It exists in various phases and forms, common ones in soil being sulphate, sulphide, elemental S, and organic S compounds. Mineral weathering and atmospheric "wet" and "dry" deposition constitute major natural sources; anthropogenic emissions and fertilizers are other sources.

Sulphur transformation processes in soils include mineralization and immobilization (Brady 1984). Mineralization of organic sulphur to inorganic forms is dependent on moisture, aeration, temperature, and pH. Soil acidification inhibits the final oxidation step to SO_4^{2-} and crop nutrition could thus be affected except that continued atmospheric deposition can provide an adequate supply. Immobilization occurs when energy rich materials are available to microorganisms and most of the available S and N have been synthesized into microbial tissue. Application of lime, on the other hand, stimulates the prodcution of SO_4^{2-} from soil organic matter and increased uptake of S by plants occurs (Biederbeck 1978).

Sulphur deficiencies are uncommon in forest ecosystems and the S in acid deposition can exceed plant requirements. The excess sulphur either cycles, accumulates, or leaches through the system as SO_4^{2-}. The leaching and adsorption of SO_4^{2-} in forest soils has been reviewed by Morrison (1984); some of these aspects have been discussed in a previous section (Section 3.3). In general, where sulphur is deposited in excess of forest requirements and soil adsorption capacity, leaching of SO_4^{2-} and associated cations will occur. If the sulphur inputs are primarily H_2SO_4 and SO_2, the acidity will lead to accelerated losses of base cations, and possibly of Al in very acid soils (Johnson and Richter 1984). Sulphate inputs to sesquioxide-containing soils will result in immobilization and, due to electro-neutrality, immobilization of the charge balancing cation and therefore limited cation leaching. When the sulphate adsorption equilibrium is attained, leaching of sulphate and the exchange of H^+ for base cations can begin (Reuss 1980). An important exception to sulphate adsorption by sesquioxides occurs in soils that have both high hydrous oxide and organic matter levels. Sulphate adsorption is decreased in this type of soil apparently due to preferred adsorption of organic molecules (Johnson et al. 1980).

3.7 PHOSPHORUS

The cycling of phosphorus in soils in relation to inputs of acidity has been reviewed by Cole and Stewart (1982). The sole source of P in soils is from primary P minerals, the predominant one probably being hydroxyapatite. This mineral is sparingly soluble and releases small amounts of phosphate to solution where it enters into labile surface-adsorbed or precipitated soluble Ca-phosphate forms. In more weathered soils, secondary P compounds of reduced solubility and occluded inorganic P may also form. Soil pH affects the dissolution of Ca phosphates and the ionic species on colloid surfaces and in soil solution. Phosphorus in solution is taken up by plants and microorganisms. The microbial population is an important factor in the redistribution and/or accumulation of organic P compounds in the soil.

Cole and Stewart (1982), from experimental and modelling information, predict that the rapid acidification of a near neutral soil will result in an initial increase in soil solution P and in soil organic P forms. With increasing acidity, the rate of microbial turnover will decrease and organic phosphate will accumulate. A second effect of increasing acidification, however, is that as solution P decreases, the microbial population will be stressed and will consequently increase the mineralization of organic P forms. Under acid conditions, the first effect will predominate. If Fe and Al minerals are present, the solubilized P may be sequestered, thus making it less available for plant uptake or flux from the soil.

In calcareous soils, acid deposition will be neutralized resulting in increased Ca^{2+} and HCO_3^- in the soil solution (Cole and Stewart 1982). Ca phosphates will be solubilized and more P in solution will be available to plants or it may be removed by leaching. If the P is not sorbed in the subsoil it may eventually be transmitted to surface water bodies and contribute to eutrophication.

In any soil, the solubility of phosphates is governed by the form and amount of material present and also by the ionic species in the soil solution. Cole and Stewart (1982) suggested that each soil situation will have to be considered separately to determine the effects of acid inputs. As with nitrogen, the main perturbation of the P cycle is use of fertilizer P (Pierrou 1979). The annual rate of fertilizer use in industrialized countries accounts for about 10% of the steady state flux between the soil and biota and approaches 50% in Europe (Richey 1983). Much of the added P is instrumental in eutrophication of lakes and coastal waters. The P thus alters the C and N cycles as well. Acid deposition will have an impact on this interaction of cycles, both on a local and global scale, but the elucidation of just what these effects are apparently requires considerably more investigation.

In summary, the main effect of acidification on soil P is decreased leaching and accumulation of organic P forms accompanying the buildup of organic matter as indicated in Section 3.1. In acid soils with high Al concentration, Al phosphates will precipitate and P availability will be limited. In calcareous soils, more P will be solubilized providing a large source for plants but at the same time, will be subject to leaching and could increase eutrophication of water bodies.

3.8 WEATHERING

Weathering includes a number of processes such as solution and hydration, hydrolysis, carbonation, oxidation, and chelation which contribute to the chemical decomposition of mineral materials. Ulrich (1980) has discussed the process of silicate weathering and its importance in H ion consumption. Much H consumption occurs during weathering of clay minerals as compared to primary silicates such as feldspars. Ulrich (1980) also indicates that clay mineral weathering is essentially aluminum buffering as follows:

$$AlOOH + 3H^+ = Al^{3+} + 2H_2O \qquad [30]$$

This buffering mechanism is important in the pH range 5 - 6.5. The rate of weathering increases with increase of H^+ concentration in solution. Stuanes (1980) showed that the rate of increase is rather modest down to pH 4.3 but that it increases markedly below pH 4.0.

Bache (1983a) has reviewed the chemistry of mineral and rock weathering and the factors which influence rates of weathering. The chemical changes which take place as water moves through soil depend mainly on the flow pathways of the water through soil and subsoil materials and on the composition of the soil and rock through which it flows (Bache 1983b). In calcareous soils any acidity reaching soils from precipitation is rapidly neutralized. In noncalcareous, slightly acid soils chemical reactions are dominated by surface adsorption and exchange processes, particularly cation exchange.

The effect of H on these processes depends on its rate of input; 1000 mm of rainfall of pH 4 would deposit 1 kmol (H^+) ha^{-1} onto the land. Bache (1983b) calculated that such rainfall would reduce exchangeable Ca and Mg and that considerable change in acidity of a soil could be expected within 100 years. This quantity of acidity in rainfall is comparable to that from natural CO_2 sources in the soil, but is less than that commonly produced by fertilizers (Bache 1980a).

In strongly acid soils, soil layers more acidic than the water percolating through will release H to lower layers. This generally applies to organic soils and surface litter layers of forest soils. The H may release Al by weathering, but the fate of the Al depends on anions in solution. The presence of SO_4^{2-} may result in precipitation of aluminum sulphate, but both Al^{3+} and SO_4^{2-} may also leach to groundwater and eventually affect surface water bodies.

Considerable quantities of weatherable minerals such as feldspars are present in the soils of a large proportion of the plains region of Alberta. Feldspars constitute from 10 to 30% of the sand fraction of glacial till materials in most of the province (Pawluk and Bayrock 1969). In northeastern Alberta, where underlying marine shales contributed significantly to glacial materials the feldspar content of till sand fractions is generally about 10% (Pawluk and Bayrock 1969; Spiers 1982). Appreciable quantities of feldspars have also been found in glaciofluvial and glaciolacustrine materials (Pawluk and Lindsay 1964; Lavkulich et al. 1964; and Arshad and Pawluk 1966). The silt fraction in soils of the prairies also has significant feldspar content (Somasiri et al. 1971; Abder-Ruhman 1980). In sand fractions, Na-Ca feldspars are predominant over K-feldspars (Pawluk and Bayrock 1969; Spiers 1982). Pawluk (1961) and St. Arnaud and Sudom (1981) found that some weathering of feldspar minerals in Orthic Gray Luvisols has occurred. It would appear, therefore, that the abundance of weatherable minerals has diminished as a consequence of soil formation. However, Abder-Ruhman (1980) found little reduction in the feldspar content of surfaces of Orthic Gray Luvisols in east central Alberta.

There is little available information about the mineralogy of soils derived from Cordilleran materials. A few studies indicate that the occurrence and content of feldspars is highly variable (Pettapiece 1970; Beke and Pawluk 1971; and Smith 1979). Mica appears to be common, but smectites are also variable in occurrence. The above workers have also identified some pyroxenes and/or amphiboles of volcanic ash origin in surface soil horizons. The quantities of these are small and their general distribution is likely sporadic.

It is thus apparent that the quantities of weatherable minerals in Alberta are significant and they probably represent a very large capacity to consume H ions. In addition, carbonates are almost ubiquitous in Alberta plains subsoils. These are important considerations in assessing the influence of acidification of soils on ground and surface waters. However, acid deposition could alter properties in the surface layers of soils and subsequently influence plant growth prior to any percolation of water into subsoils of higher neutralizing and buffering capacity. Bache (1980a) has reviewed the effect of pattern of infiltration and flow on reaction of acidified water with soil. The effects of water flow and water balance, including factors such as evapotranspiration, are discussed in Section 3.10.3.

3.9 NEUTRALIZATION OF SOIL ACIDITY

Various attributes of soil and of atmospheric deposition tend to retard or counteract acidification of soils. A soil component of major importance is calcium carbonate. Application of $CaCO_3$ (liming) is a common practice on agricultural soils in many parts of the world. The mechanisms through which $CaCO_3$ reacts with acid soils are complex, and the rates of neutralization and the final reaction products are not known with certainty. In water, $CaCO_3$ dissolves and OH^- ions are generated as follows (Bohn et al. 1979):

$$CaCO_3 + H_2O = Ca^{2+} + HCO_3^- + OH^- \qquad [31]$$

If all the $CaCO_3$ reacts with H ions, 1 kmol of $CaCO_3$ would neutralize 2 kmol of H. According to this reaction a layer of soil 5 cm thick with a bulk density of 1.3 and a $CaCO_3$ content of 1% would neutralize 130 kmol ha^{-1} of H (Holowaychuk and Lindsay 1982). Thus, applying the commonly used figure of 1 kmol ha^{-1} y^{-1} input of acidity, it would require somewhat more than a century to dissolve the available carbonate.

Entrainment of slightly acid to mildly alkaline dust or other constituents is a common occurrence in the cultivated portions of the Interior Plains (Gorham 1976; Caiazza et al. 1978). Holowaychuk and Lindsay (1982) reported that considerable dust fall occurred in the Edmonton area during May 1981. The dust apparently originated in southeastern Alberta and southwestern Saskatchewan. It had a pH of 6.9. Dust storms are a common occurrence in the southern Prairies, and severe storms have occurred in southern Alberta in recent years. Dust fall materials would tend to neutralize airborne and soil acidity. Bache (1980b) and Wiklander (1975) have also indicated that the presence of neutral salts in acid deposition would have a moderating influence on acidifying effects.

Holowaychuk and Lindsay (1982) have suggested that surface and groundwater discharge in low lying landscape positions can provide minerotrophic waters which contribute to neutralization of acid deposition. This effect may be important in organic soils, particularly those of minerotrophic peatlands such as fens and swamps in which soil pH values are about 6 or higher. These soils have a high content of bases while sphagnum bog soils are oligotrophic, having low base contents. The minerotrophic water of fens is at least one factor contributing to higher base status and pH in fen soils. Erosion of land is another means by which acid deposition effects on soils can be counteracted. Dust fall, resulting from local and regional wind erosion, was discussed above. Water erosion is also considered a major problem in parts of Alberta. Through transport of soluble materials and of organic and inorganic particulates, erosion can contribute substantially to the neutralizing capability of soils in lower lying areas. Simultaneously, more base rich and possibly calcareous materials can be exposed in upper slope positions. The neutralizing influence can therefore be substantial, but erosion is highly undesirable from the standpoint of maintaining soil fertility and productivity, and of maintaining stable landscapes.

The influence of weathering and cation exchange in consuming H has been discussed in previous sections. Recycling of nutrients by vegetation, also discussed previously, can also compensate for some leaching losses and thus moderate the effects of acidification to various extents (McFee et al. 1976; Wiklander 1979; and Ulrich 1980).

In general, grassland and deciduous forest ecosystems are more effective in this respect than coniferous ecosystems.

3.10 EFFECTS OF ANTHROPOGENIC SOURCES OF ACIDITY

3.10.1 Nitrogenous Fertilizers

The gradual acidification of soils as a result of nitrification of ammonium based fertilizers has been extensively studied (citations in McCoy and Webster 1977). The reactions of fertilizer nitrogen with soil components have been reviewed by Penney and Henry (1976). Application of fertilizer N in the form of urea or anhydrous ammonia leads to a temporary increase in pH through the initial formation of NH_4^+ as follows:

$$CO(NH_2)_2 + H_2O \xrightarrow{urease} 2NH_3 + CO_2 \quad [32]$$

$$NH_3 + H_2O = NH_4^+ + OH^- \quad [33]$$

The oxidation of NH_4^+ to NO_2^- by Nitrosomonas is then carried out with the production of 2 moles H^+/mole NH_4^+:

$$2NH_4^+ + 3O_2 = 2NO_2^- + 2H_2O + 4H^+ \quad [34]$$

The NO_2^- is then converted by Nitrobacter to NO_3^-:

$$2NO_2^- + O_2 = 2NO_3^- \quad [35]$$

Of the forms of N fertilizers, ammonium sulphate has the highest equivalent acidity requiring a $CaCO_3$:N weight ratio of 5.35 for neutralization (Penney and Henry 1976). Anhydrous ammonia, urea and ammonium nitrate have a ratio of 1.80 for neutralization. The actual acidifying impact is determined by various factors as follows: proportion of added NH_4^+ used by a crop before nitrification; NH_4^+ and NO_3^- concentration; pH; oxygen supply; and temperature (Alexander 1977). Under field conditions, fixation and leaching of NH_4^+, leaching of NO_3^-, and the influences of these and of plant growth on leaching of bases influence the amount of acidity produced. Because of these many factors, actual acidification under field conditions has usually been determined empirically. Examples of such acidification have been reviewed by McCoy (1973) and Penney and Henry (1976).

The problem of acidity in agricultural soils of Alberta and other western provinces has been reviewed by Penney et al.(1977) and more recently by Hoyt et al. (1981). The acidification of soils was attributed primarily to use of fertilizers although industrial emissions were cited as another possible cause. Acidification of soils due to fertilizers has been demonstrated by field experimentation in Alberta. Cairns (1971) reported that the application of high rates of ammonium phosphate-sulphate (16-20-0) fertilizer to a Solonetzic soil near Vegreville lowered the pH from 5.8 to 4.7 in 10 years. Annual applications to the same soil of $(NH_4)_2SO_4$, NH_4NO_3, and urea at 112 kg N ha^{-1} for 10 years reduced pH levels from 5.6 to 4.4, 4.9, and 5.3, respectively

(Perl et al. 1982). Low rates of NS, NPS, and NPKS fertilizers applied to Breton soil, a medium textured Gray Luvisol, also lowered the soil pH (McCoy and Webster 1977). Over a 40 year period, fertilizer N at 11 kg ha^{-1} and S at 9 kg ha^{-1} caused the soil pH to decrease from 5.8 to 5.3. Nyborg and Mahli (1981) showed that high rates of fertilization of the Breton soil with ammonium nitrate, urea, and ammonium sulphate not only significantly reduced the pH of topsoil but that of subsoil (15-30 cm) as well. Hoyt et al. (1981) reported Al solubilization accompanying pH reduction in field fertilization trials in the Peace River region. Ross et al. (1985) recently reported substantial soil acidification of orchard soils in the Okanagan Valley resulting from fertilization.

Hoyt et al.(1981) estimated the amounts of cultivated land with acid soils on the prairies as shown in Table 2. Little information about the acidity of soils prior to cultivation is available, so the proportions of soils in Table 2 acidified due to fertilization are unknown. Acid soils were considered by Hoyt et al. (1981) to be those soils with pH 6.0 and less. The percentage of soils acidified to pH 6 or less on a provincial soil test area basis was demonstrated by Penney et al. (1977). These two papers should be consulted for detailed discussion of the extent of acidification in Alberta.

Hoyt et al. (1981) provided forecasts of continued acidification which, though tenuous, indicate cause for alarm. They suggested that about 160,000 ha of acidic and potentially acid soils could develop depressed soil pH of 0.25 units in about 15 years as a result of SO_2-S emitted from industrial sources in agricultural areas. They also projected that there will be an increase of about 1 million ha of acid soil (pH = 6.0) in the period 1972 to 1985 resulting from use of fertilizers. It was predicted that about 25% of soils in Alberta, and over 40% of soils in the Peace River region will have become acidic by 1985. The implications to agriculture and means of rectifying the problem were also discussed by Hoyt et al. (1981).

Although a review of acidification of soils due to fertilization may not be relevant to the question of acidification resulting from atmospheric acid deposition, a discussion of the topic is necessary to place acid deposition effects in perspective. Tabatabai (1985) indicated that the potential acidifying effect of 140 kg ha^{-1} of anhydrous ammonia would produce a soil impact of 100 $kmol(H^+)ha^{-1}$ y^{-1}. The projections of Hoyt et al.(1981) were based on a decrease of 0.5 pH unit over 40 years caused by N applied at 22.4 kg N ha^{-1} y^{-1} (in turn based on work of McCoy and Webster (1977) at the Breton plots). The projected input of SO_2-S in Alberta over 15 years is about 300 kg ha^{-1} or an equivalent of about 0.5 $kmol(H^+)$ ha^{-1} y^{-1} (over a 400,000 ha area of land adjacent to emitters). It is suggested that this level will depress the soil pH by 0.25 units in 15 years. Such a drop (0.25 units), as suggested by Tabatabai (1985) may not be significant because spatial and temporal variation in soil pH is probably higher than 0.25 units. The assumed rates of fertilizer application can clearly be seen to be several times the projected levels of SO_2-S inputs. The equivalent acidity of 22.4 kg N ha^{-1} y^{-1} is 10 to 20 times that due to the calculated input of SO_2-S. Moreover, the actual rates of fertilization may be much higher than this assumed rate (although, due to differing farming practices, summerfallowing, and other factors, lower average rates are also likely). In a review of effects of acid forming emissions by the Environmental Council of Alberta, the $CaCO_3$ equivalent required to neutralize atmospheric sources of acidity

Table 2. Estimated amounts of cultivated land in different ranges of soil pH on the Great Plains.[1]

Province or Region	Hectares (x 1000)		
	pH <5.5	pH 5.6-6.0	pH 6.1-6.5
Manitoba		10[2]	
Saskatchewan	202	202	405
Alberta, excluding the Peace River region[3]	230	1166	2276
Peace River region of Alberta and British Columbia[3]	98	447	602
TOTAL	530	1825	3283

[1] Adapted from the original table in Hoyt et al. (1981).

[2] pH <6.0.

[3] Based on soil samples taken during 1962-72.

was indicated to be 2 kg ha^{-1} as compared to 51 kg ha^{-1} for neutralizing fertilizer acidity (Simpson-Lewis et al. 1983, cited by Sanderson 1984). These figures, based on data from the 1970's, indicate that fertilizers contribute 25 times the acidity contributed by atmospheric emissions.

Hoyt et al. (1981) suggested that liming should become a general practice for solving soil acidity problems. They provided evidence for increase in productivity due to liming and indicated probable recouping of liming costs in about two years. In view of the projected liming practices required to rectify acidification due to fertilization, it is suggested that the much smaller inputs of acidity due to SO_2 and NOx deposition does not constitute a serious problem in soils used for annual crops or for cropping systems including hay or pasture rotations. Over the long term, acidification could become serious in areas of sensitive soils under rangeland or forest (in which liming will likely remain uneconomical). With regard to agricultural soils, others have recently concluded that due to liming practices, SO_2 and NOx will not be considered as threats to productivity, and additions of S and N may in fact be beneficial for plant growth. In a study in West Germany, where local S deposition rates vary from 20 to 100 kg S ha^{-1}, little direct damage to field crops by SO_2 could be found (Sauerbeck 1983). Little loss of cations was expected from most soils being farmed. It can be concluded from these various reports that agricultural soils will not suffer from long-term inputs of acidic deposition where fertilization and liming are practised. These conclusions, however, are made from a viewpoint of soils effects only and do not consider possible direct effects of acid forming substances on vegetation (which are subjects of other reviews in the ADRP).

3.10.2 Atmospheric Deposition

The main precursors of acid forming atmospheric pollutants in Alberta are anthropogenic emissions of SOx, reduced sulphur compounds, and NOx (Hunt et al. 1982). The removal mechanisms of material from the atmosphere are complex processes generally placed in categories referred to as wet and dry deposition. Within these are subcategories of mechanisms by which materials reach plant and soil surfaces (Fowler 1980; Galloway and Parker 1980):

1. Wet deposition
    a. Incident wet deposition - gravitational transfer of water to earth surfaces
    b. Throughfall - water that has passed through a leaf canopy
    c. Net throughfall - difference between throughfall and incident deposition for a particular area.
2. Dry deposition
    a. Dry fallout - soil and seasalt particles of >10-30 µm diameter which settle by gravity.
    b. Aerosol impaction - particles of <10 µm diameter which impact or deposit onto surfaces. These are commonly particles of $(NH_4)_2SO_4$, NH_4NO_3, and others.
    c. Gaseous adsorption - gases sorbed by foliage or soils (i.e., SO_2, NOx, CO_2).

Dry deposition is probably the most important atmospheric removal process for SO_2. Dry deposition measurement is difficult as compared to wet deposition and little reliable data for the province has been obtained (Sandhu et al. 1980). Wet and dry deposition measurement methods, transport, reactions, and other aspects of atmospheric pollutants are subjects of other reviews in this project. Recent reviews of deposition mechanisms and interactions of gaseous and particulate materials in relation to plant and soil surfaces include those of Fowler (1980), Chamberlain (1986), and Weidensaul and McClenahen (1986).

The concept of resistance has been used in mathematical descriptions of flux of airborne gaseous substances to surfaces (Fowler 1980). That is, different substances have different resistance factors to deposition which can be empirically determined. Properties of the deposited substance itself and meteorological conditions also have resistance factors. Surface resistances of soils have not been measured due to their heterogeneity, but calcareous soils apparently have negligible surface resistance. However, resistance increases with decreasing pH and increasing dryness. More gases will be sorbed by soils of high moisture content because the resistance of water is negligible, at least for SO_2, NO_2, and HNO_3. Other gases which can be adsorbed include nitrous oxide, nitric oxide, hydrogen sulphide, methyl mercaptan, dimethyl disulphide, carbonyl sulphide and carbon disulphide (Committee on the Atmosphere and the Biosphere 1981).

Particulate dry materials are deposited by impaction and gravitational forces unless the diameter is less than 1 µm, in which case transport occurs by Brownian movement. Deposition rates thus increase with increasing particle size and also with increase in roughness of the surface. This latter factor is important because particles, upon deposition, may be returned to the free atmosphere by bounce-off or blow-off unless obstacles are encountered (Fowler 1980).

With regard to wet deposition, both gaseous and particulate materials can be incorporated in cloud droplets. Particulates in fact may act as cloud condensation nuclei. The solution and oxidation of gases such as SO_2 and NO_2 by cloud and rain droplets has been described by Fowler (1980).

As indicated previously, little data for dry deposition quantities are available in Alberta. Total deposition has been measured in some studies, and gaseous sorption measurement by plant and soil surfaces has been the object of others. Caiazza et al. (1978) found dry:wet deposition ratios of 4.8 for sulphate and 5.6 for unfiltered total N in the Edmonton area.

A greater role of dry deposition in atmospheric inputs than had previously been considered was recently reported for a mixed hardwood forest in the eastern United States (Lindberg et al. 1986). Precipitation was found to be the most important deposition process for SO_4^{2-} and NH_4^+, dry deposition of vapours was most important for NO_3^- and H^+, and dry deposition of coarse particles was most important for K^+ and Ca^{2+}. Total and dry deposition amounts were found to be underestimated significantly by standard bulk deposition collectors.

Chaudry et al. (1982) reviewed some aspects of reactions of atmospherically deposited sulphur with soils. Extensive literature on the subject has shown that soils generally have a high sulphur sorption capacity. The moisture content of soil, among other factors, was found to influence the amount and rate of S sorbed. Nyborg et al. (1977, 1980) and Hsu and Hodgson (1977) have demonstrated in a number of experiments that Alberta soils have high capacities for sorbing S from the air and that soil pH can be depressed as a result. Total S gains of 12 to 53 kg ha^{-1} were reported for sites downwind from SO_2 emitters. The distances from SO_2 emitters ranged from 2 to 37 km; the highest S gains were obtained for soils nearest and furthest from the emitters, while intermediate distances were somewhat lower (Nyborg et al. 1977). Generally, little of the sorbed S was found in SO_4^{2-} form. In addition, it was found that snowpacks had low S contents (<1 kg ha^{-1}), rainfall contributed up to 4 kg S ha^{-1} y^{-1} near emitters, water surfaces sorbed 4 to 15 kg S ha^{-1} y^{-1}, and forest throughfall had S contents 3 to 4 times greater than incident wet deposition (Nyborg et al. 1977).

The S forms were not identified in the experiments above. In chamber studies of SO_2 and NO_2 sorption, Ghiorse and Alexander (1976) suggested that some of the non-sulphate S was in organic forms. These authors found experimental evidence that the initial products of SO_2 sorption were sulphite, bisulphite, and hydrogen ions. These rapidly converted to SO_4^{2-} in O_2-containing soil water. The investigators speculated that organic S may form due to sorption sites on organic matter or to the presence of carbonyl groups with which sorption products can form sulphite-addition compounds. They suggested that the role of microflora is a passive one in which substances with which SO_2 can react are produced.

In NO_2 sorption studies, microflora were found to have an active role (Ghiorse and Alexander 1976). In sterile soil, NO_2 was initially converted nonbiologically to both NO_2^- and NO_3^-. Nitrification was incomplete in sterile soil samples, but in non-sterile samples, nitrifying microorganisms converted almost all NO_2 to NO_3^-, and nitrification of native soil N was apparently stimulated.

Some limitations were indicated in the studies of Nyborg et al. (1977, 1980) discussed above. The method of total S determination was considered to be imprecise. The pH depressions of 0.1 or 0.2 units were recognized as being within normal spatial and temporal variability of this soil property. In addition, the errors involved in calculating S deposition on a kg h^{-1} basis could be large due to large multiplication factors involved in converting from measurements of small quantities of soil. Thus, the results of SO_2 deposition and acidification studies are only approximate, but do demonstrate a potential for acidification of soils. Further research not only into levels and types of deposition but of mechanisms of sorption and transformations in soils appears to be desirable. Knowledge and investigation of these aspects has been hampered, to date, by inadequate data of quantities and types of pollutants in air.

In most natural and agricultural ecosystems, air pollutants will first encounter vegetation surfaces. These, like soil, have a tremendous SO_2 sorption capacity which diminishes with time of exposure. Coniferous trees apparently can accumulate much more sulphur than decidous species (Horntvedt et al. 1980). Interactions of acid forming deposits with vegetation are not the subject of this review, but it is evident that studies of soil effects must take this factor into account. Indeed, in natural and agricultural ecosystems, it would be desirable to conduct integrated rather than independent studies of these components. A general conclusion of this brief review is that sorption mechanisms and reactions of acid forming substances in soils are not well understood and further research specific to situations in Alberta is desirable.

3.10.3 Other Factors Affecting Fate of Acid Forming Substances in Soils

Several factors affect the ultimate soil acidifying influence of atmospheric deposits. The role of water movement in soil, for example, has been reviewed by Bache (1980a). The effect of a reacting soil solution will depend on the pattern of infiltration and flow through the soil. This is generally determined by the structure of the soil in each layer and by the rate of application of water. Bache (1980a) concludes that more influent solution will react with soil surfaces at low infiltration rates than at high infiltration rates. In field situations, amounts of surface runoff, lateral flow, and channel flow are determining factors.

Components of the water balance in an ecosystem will also influence the transport and transformation of acid deposition. In areas where evapotranspiration exceeds precipitation, materials from rainfall are not moved to the subsoil but are accumulated (Reuss 1980). If the excess of evapotranspiration over precipitation was consistent and continuous, only accumulation would occur. However, in most areas, precipitation varies such that there may at times be sufficient soil input to leach materials to subsoils. In a study of Brunisolic sandy soils under jack pine forest in northeastern Alberta, McGill et al. (1980) reported that rainwater percolated below the root zone only when precipitation exceeded 30 mm over several days. On an annual basis, drainage accounted for 20 to 40% of input water at different locations. It was considered that the water content of the snowpack plus precipitation occurring during and immediately following the thaw was the prime input to deep soil drainage. In addition, during the growing season, it was found that about 40% of rainfall is intercepted by the canopy and the soil litter layer from which it re-evaporated. Thus, little moisture entered the mineral soil during most (over half) rainfall events. In this type of water balance situation, atmospheric deposits would be expected to accumulate in upper litter and mineral soil horizons over most of the year. During spring thaw and episodes of high rainfall, a substantial proportion of accumulated materials may be flushed down to lower soil layers and possibly to the water table.

Snow composition and snowmelt have been found to be important factors in acidification of snow and natural waters. Studies in the SNSF project (Overrein et al. 1980) demonstrated that lakes and rivers show particularly low pH values during snowmelt. Moreover, the first fractions of meltwater contain higher concentrations of ions than the bulk snow. The composition of runoff is considerably changed by contact with soil and vegetation. Estimates of effects of snowmelt on water bodies, as well as on soils and vegetation, require data on surface runoff, subsurface flow, and deep drainage. Water and wind erosion are other factors (discussed in previous sections) which influence the fate of atmospheric deposition.

In conclusion, not only soil chemical processes but soil physical factors, water dynamics, and landscape processes influence the transformations and movements of acidifying substances. Studies including all of these factors will be necessary in any thorough investigation of acid deposition impacts on soils.

3.11 SUMMARY

A summary of potential impacts of acid deposition on soils is given in Table 3. The listing is derived in part from McFee (1982) and from Cook (1983).

Table 3. Summary of the potential impact of acid deposition on soils.

Process or Property	Hypothetical Impact of Acid Deposition
I. Soil Exchange Complex	
Exchange Capacity	Decrease in CEC resulting from clay alumination Increase in CEC of soils with oxy-hydroxides due to sulphate adsorption
Exchangeable Acidity	Increase
Base Saturation	Decrease
Clay Mineral Morphology	Increased formation of hydroxy-Al interlayers and acid weathering
Aluminum	Increased mobilization and leaching Increased availability and toxicity
II. Organic Matter	
Organic Matter Turnover	Decreased rate of C mineralization due to acidification and/or associated trace metal toxicity Decreased CO_2 flux from land to atmosphere Increased retention of organic matter
Microbial Community Dynamics	Shift from bacteria to more acid - tolerant fungi
Organo-Mineral Associations	Reduced organo-clay interaction due to disruption of cation bridge linkages
Root Uptake	Trace metal toxicity due to acidification
III. Plant Nutrients	
Nitrogen	Decreased ammonification Decreased nitrification Changes in products of denitrification Increase in leaching Enhanced cation leaching due to NO_3^- inputs Reduced plant availability

continued...

Table 3 (Concluded).

Process or Property	Hypothetical Impact of Acid Deposition
Sulphur	Increased SO_4^{2-} reduction in low S, anoxic systems Increased reduced-S flux and reduced CH_4 flux to atmosphere Decreased leaching of S Decreased leaching of cations in sesquioxidic soils; increased leaching in others Reduced plant availability
Phosphorus	Decreased leaching and AlPO4 precipitation in soil with high Al Increased PO_4^{3-} solubilization, plant availability and leaching in calcareous soils Reduced availability with pH reduction
Fe, Mn, Zn, Cu, Co	Increased availability Increased leaching
Mo, B	Reduced availability
Ca, Mg, K	Reduced availability Increased leaching
Toxic Elements	Some micronutrients may reach toxic levels due to increased solubility Increased concentrations, toxicity and leaching of heavy metals Increased Al toxicity
IV Weathering	
Carbonates	Increased dissolution
Primary Minerals	Increased dissolution
Clay Minerals	Increased alumination (formation of Al interlayers) Reduced surface charge

4. OVERVIEW OF SOILS IN ALBERTA

4.1 INTRODUCTION

Alberta is naturally divided into four major regions based on distinctive land forms and geologic structure. The northeast corner of the province which consists of rugged, rolling terrain of exposed Precambrian rock is part of the Canadian Shield. Most of the province is within the level to hilly Plains region which consists of soft, flat-lying sandstones and shales covering the Precambrian basement and is generally overlain by glacial drift. In western Alberta, the bedrock is folded and tilted into a series of long ridges which form the Foothills belt. Beyond the Foothills lies the Cordilleran region which is chiefly made up of the front ranges of the Rocky Mountains.

The climate of the province is generally dry and sunny. Precipitation may vary greatly from about 17 cm in the Medicine Hat area to more than 50 cm a year in the foothills. Drought and hail storms are common in southern regions. Frost-free periods range from 110 days at Lethbridge to 65 days in the north. Temperatures also vary dramatically rising to 38°C or more in the southern part of the province and frequently dipping to less than -40°C in the northern regions. Chinooks (warm winds) occur periodically in the south during the winter and may raise the temperature considerably.

Each of major regions has unique types and assemblages of soils. In the northern Plains, Foothills and Cordilleran regions, soils of the Luvisolic, Brunisolic, Organic, and Cryosolic orders occur beneath spruce, pine, aspen, fir, and mixedwood forests. The Parkland of the central Plains region is characterized by soils of the Chernozemic and Luvisolic orders. The southern Plains are characterized by graminoid vegetation and are dominated by soils of the Chernozemic and Solonetzic orders. Soils of the Gleysolic and Regosolic orders can occur in association with any of the other soil orders; to some extent, this is also true of Solonetzic soils. Estimates of areas of soils in each of the orders in Alberta are given in Table 4.

While most of Alberta can be described as consisting of forested, parkland, or grassland types of natural ecological systems, anthropogenically influenced lands can be considered to constitute a fourth major system. For the most part, these are composed of agricultural (or agro-) ecosystems with wheat, barley, oats, rye, oilseeds, and hay as the most common crops. Areas of different types and uses of farmland, forest, and lakes and barren areas are given in Table 5.

4.2 THE SOIL PROFILE

The profile is a vertical section of soil extending down through all its horizons into the unweathered material. Soil horizons may differ in colour, texture, structure, consistence, reaction, thickness, or any combinations of these. Usually horizons also differ in chemical and biological composition. A diagrammatic representation of a soil profile is shown in Figure 3. Various terms used in describing soil horizons are included in the figure and are described in the Glossary (Appendix Section 9.2). More detailed information about soil profile description may be found in The Canadian System of Soil Classification (Expert Committee on Soil Survey 1978).

Table 4. Areas of the soil orders in Alberta.[1]

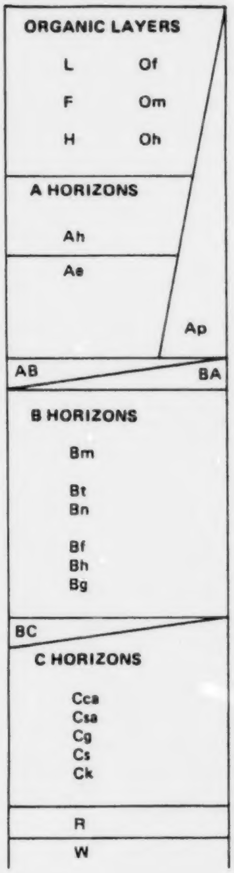
Soil Order	Area (km^2 x 1000)
Chernozemic	141.5
Solonetzic	43.0
Luvisolic	203.1
Brunisolic and Podzolic	52.9
Regosolic	7.4
Gleysolic	21.6
Organic	104.6
Cryosolic	43.9
Nonsoil - Rockland, Icefields,	26.4
- Freshwater	16.8
Total	661.2

[1] Adapted from Holowaychuk and Fessenden (1986)

Table 5. Types and uses of land in Alberta.[1]

Land Type	Area (km^2 x 1000)	Percent of Total
Farmland		
Improved		
Crops Wheat	27.2	4.1
Barley	26.0	3.9
Hay	14.1	2.1
Canola	5.9	0.9
Oats	5.3	0.8
Other	6.0	0.9
Total	84.5	12.7
Pasture	15.8	2.4
Summerfallow	22.0	3.3
Other	3.0	0.5
Total	125.3	19.0
Unimproved	75.0	11.4
Total	200.3	30.3
Wildland		
Forest		
Productive timber	207.4	31.4
Potentially productive	87.6	13.2
Muskeg	73.6	11.2
Total	368.6	55.8
National Parks	63.0	9.5
Provincial Parks	2.3	0.3
Water, Rockland	27.0	4.1
Total	460.9	69.7
Total	661.2	100.0

[1] Adapted from Alberta Agriculture (1981) and Dermott (1982).



L-F-H	well drained decomposing plant litter, primarily leaves, twigs, woody materials. L - slightly decomposed, F - partly decomposed, H - well decomposed.
O	poorly drained decomposing peat, mainly mosses, rushes, woody materials. Of - fibric - least decomposed; Om - mesic - moderately decomposed; Oh - humic - most highly decomposed.
A	Organic-mineral horizons at or near the surface. Ah - dark colored, humus-rich horizon Ae - light colored, eluviated horizon, characterized by removal of clay, iron, aluminium or organic matter, alone or in combination. Ap - horizons disturbed by man's activities, that is, by cultivation, or pasturing, or both.
AB, BA	horizons transitional to A and B.
B	a mineral horizon differing from A and C by the following characteristics: m - slightly altered by hydrolysis, oxidation, or solution or all three, to give a change in color, or structure or both. t - a significant accumulation of silicate clay. n - a columnar or prismatic structure, hard consistence when dry and significantly high exchangeable sodium. f - a significant accumulation of Fe + Al combined with organic matter. h - a significant accumulation of illuvial organic matter. g - a significant expression of gleying.[2]
BC	a horizon transitional to B and C.
C	a horizon comparatively unaffected by soil forming processes, except for: ca - an accumulation of lime. sa - an accumulation of water-soluble salts. g - a significant expression of gleying. s - denotes the presence of salts, including gypsum ($CaSO_4$). k - denotes the presence of lime.
R	a consolidated bedrock layer.
W	a layer of water.

NOTE: The lower case letters shown above in the A, B and C horizons are sometimes combined to express combinations of characteristics. Other lower case letters not listed above are:

b - a buried soil horizon.
c - an irreversibly cemented horizon.
j - a modifier of suffixes e, f, g, n and t to denote expression of, but failure to meet, the specified limits of the suffix it modifies.
u - a horizon markedly disrupted by physical or faunal processes other than cryoturbation.
x - a horizon of fragipan character.
y - a horizon affected by cryoturbation.
z - a perennially frozen layer.

Figure 3. Diagram of a soil profile and definitions of soil horizon symbols.

4.3 TERMINOLOGY FOR DESCRIBING SOILS

Numerous terms and classification systems have been developed for description of soils. Examples are texture, structure, colour, drainage, pH, calcareousness, salinity, mineralogy, nutrient classes, and others. Definitions and descriptions of classification schemes can be found in Canadian Society of Soil Science (1976) and Day (1983). A glossary of terms and definitions used in peatland description has been prepared by Stanek and Worley (1983). Definitions and class limits of terms used in this report are provided in the Glossary (Section 9.2).

4.4 SOIL FORMATION

Soil is the naturally occurring, unconsolidated, mineral or organic material at the earth's surface that is capable of supporting plant growth (Canadian Society of Soil Science 1976). Soil formation or genesis is the process or combination of processes responsible for the development of soil. At any particular location, soil genesis results in a particular type of soil with distinctive morphological and chemical characteristics. These characteristics are the result of the integrated effects of the soil forming factors: climate, parent material, biota, topography, and time (Jenny 1941). Soils do not cease to form, but are continually changing systems which respond to any changes in the environment. Detailed discussion of soil formation can be found in Buol et al. (1980). Properties and processes of forest soils have been discussed by Armson (1977).

Parent material, topography, and time are referred to as the passive factors of soil formation as they do not form soils without the active factors of climate and biota. Parent materials in Alberta may be of two general kinds, mineral and organic. The most common mineral materials are morainal, glaciolacustrine, glaciofluvial, and eolian. Colluvium and bedrock are common in the mountains, and in eroded scarps and valleys. Organic materials are subdivided into three classes: bog, fen, and swamp. Definitions of these parent material classes can be found in the Glossary (Appendix Section 9.2) and in Expert Committee on Soil Survey (1978).

Topography refers to the surface features of the land, especially its relief and contours. It includes features such as slope, aspect, and landform. Topography is considered to be a passive factor of soil formation which modifies the effects of climate by influencing, for example, soil drainage, soil temperature, and vegetation. All of the ten slope classes outlined in Expert Committee on Soil Survey (1978) are found in the varied terrain of the province. Classes of landforms, or surface expression, found in Alberta include: apron, blanket, fan, hummocky, inclined, level, rolling, ridged, steep, terraced, undulating, and veneer. Classes for organic terrain are: blanket, bowl, domed, floating, horizontal, plateau, ribbed, and sloping. Definitions of these classes can be found in Expert Committee on Soil Survey (1978).

Climate is an active factor of soil formation in that it determines the amount, distribution, and kind of precipitation as well as the amount and distribution of solar energy available at any point in the landscape. It influences plant growth, evapotranspiration, leaching, weathering, and most other soil processes. Description of soil climate is based on soil moisture and temperature regimes in relation to periods of biological significance such as growing season. Seven major soil temperature classes and ten soil moisture subclasses are recognized (Clayton et al. 1977). The main soil temperature classes in Alberta are subarctic, cryoboreal, and boreal. Three aquic moisture regimes (peraquic, aquic, and subaquic) and five moist unsaturated regimes (perhumid, humid, subhumid, semiarid, and subarid) occur in Alberta. Arid and xeric regimes are not considered to occur extensively anywhere in Canada. Clayton et al. (1977) should be referred to for definitions and criteria of each class.

Biota is another active factor in soil formation which, in conjunction with climate, modifies the parent material to produce soil. The kinds of soils that form are influenced by the types of organic matter produced and the cycling of nutrient elements by different types of macro- and microbiota. One broad but usually valid generalization is that forest vegetation in Alberta tends to accumulate organic material on top of mineral soil where it decomposes and releases organic acids to the layers below. These then participate in the weathering of soil minerals. Grassland vegetation, on the other hand, has extensive root systems which die back and bring about accumulation of organic matter in the mineral soil. In both situations, microorganisms and microfauna act in decomposition of organic materials and additionally can make nutrients available for plant growth through N fixation and other mechanisms.

The major types of native vegetation reflect the broad differences in climate that occur in Alberta. The combined influences of these is reflected by the recognition of several major ecoregions (Strong and Leggat 1981). These correspond to the major soil zones, particularly in the grassland regions. It is beyond the scope of this report to describe the types and influences of flora, fauna, and microorganisms which contribute to formation of different kinds of soils in Alberta. General information about these can be found in Government and University of Alberta (1969), North (1976), Strong and Leggat (1981), and Knapik (1984). Moreover, vegetation, soil microbiology, and the influences of acid deposition on them, are subjects of other reviews in the Acid Deposition Research Program.

Information about agricultural crops is included in Table 5 (Section 4.1). Characteristics of agroecosystems are the subject of a separate review, and are also briefly discussed in the following sections dealing with soil orders.

Soils of Alberta, and of the Canadian prairies generally, have had a relatively brief period of development. As a consequence only the most permeable soils are relatively depleted in bases. Argillic horizons are characteristic of most forest soils. These diminish rates of water movement and deep leaching of bases is consequently hindered. However, surface eluviated horizons are generally impoverished of clay minerals, organic matter, and nutrients. Grassland soils are characterized by accumulation of humus and continuous recycling of nutrient elements. Over the period of their development only readily soluble materials such as salts and carbonates have been moved to lower soil layers.

Soils in Alberta have had less than 14,000 years to develop. The retreating edge of the Wisconsinan continental ice margin is considered to have been positioned at the extreme southern end of Alberta about 14,000 BP (before present) to 13,500 BP (Clayton and Moran 1982). The frontal ice margin was located in central Alberta about 12,000 BP to 11,000 BP and was still positioned at Lake Athabasca about 10,000 BP (Prest 1969; Christiansen 1979). Only the Cypress Hills are thought to have been free of ice during glaciation, although fresh parent materials were nevertheless developed during this period as a result of erosion and redeposition of loess. New parent materials are also continuously produced in regimes of eolian, alluvial, and colluvial activity. The soils of Alberta, thus, range in age from zero to about 14,000 years. The Rocky Mountain and Foothills regions were glaciated by the Cordilleran ice sheet which has receded to the extent that only a few areas of glaciers at high elevations still occur today.

Changes in the course of soil development have occurred as a consequence of anthropogenic activities. Man's activities are sometimes considered to be a sixth factor of soil formation. These activities have resulted in changes in rates of soil processes. In extreme cases, the results of soil genesis have been undone as, for example, erosion of soil and subsequent creation of new parent material by exposure and by redeposition. In other situations, processes of soil formation have been accelerated. The acidification of topsoil and increased leaching of bases resulting from fertilizer or atmospheric acid inputs are examples of this type of situation. After a period of development, many soils are considered to have attained a steady state; that is, a state in which there is no apparent change in appearance or in measureable properties of the soil (Lavkulich 1969). The effect of human activities is to disturb the steady state such that rates of processes change until a new steady state is reached. The prediction of changes in processes and properties, and of the time a soil impacted by acid deposition and other disturbances requires to attain a new steady state, is among the challenging problems of pedological science.

4.5 CHERNOZEMIC ORDER

4.5.1 General Description

Soils of the Chernozemic order have developed in well to imperfectly drained conditions, under xerophytic or mesophytic grasses and forbes, or under forest-grassland transition vegetation, in cool to cold, subarid to subhumid climates. According to the Canadian system of soil classification (Expert Committee on Soil Survey 1978), soils of the Chernozemic order are those which have an A horizon in which organic matter has accumulated (Ah, Ahe, Ap) and that meets the requirements of a chernozemic A horizon with properties as follows: it is at least 10 cm thick; its colour value is darker than 5.5 dry and 3.5 moist, and its chroma is less than 3.5 moist; its colour value is at least one Munsell unit darker than that of the IC horizon; in cultivated soils, the Ap must be thick and dark enough to provide 15 cm of surface material that meets the preceeding colour criteria; it contains 1-17% organic C and its C:N ratio is less than 17; usually it has sufficiently good structure so that it is neither massive and hard nor single grained when dry; its base saturation (neutral salt) is more than 80% and Ca is the dominant exchangeable ion, and; it is restricted to soils having a mean annual temperature of 0°C or higher and a soil moisture subclass drier than humid. Chernozemic soils may have an Ae horizon and a Bm or Bt horizon. They may also be gleyed but not to an extent to meet criteria of Gleysolic soils.

4.5.2 Distribution and Extent

Chernozemic soils account for about 141,500 km^2 of Alberta's land area. Their extent in the different great groups is as follows: Brown - 30,700 km^2; Dark Brown - 40,500 km^2; Black - 60,500 km^2; and Dark Gray - 6900 km^2 (Holowaychuk and Fessenden 1986).

These soils occur in the south and south central part of the province. Nearly all of the Chernozemic soils lie south of 56 °N latitude and east of 115°W longitude. In the south, these soils extend to the foothills. The Black soil zone extends approximately from 54°N latitude to 51°N latitude and occurs in patches in the southwest along the foothills. Dark Gray Chernozemic soils occur north and west of the Black soil zone. Brown and Dark Brown soils are found south and east of the Black Soil zone.

4.5.3 Genesis

Chernozemic soils in Alberta have predominantly developed on materials of glacial origin which were deposited during the last ice age. The glacial drift is sorted to various degrees and is associated with several kinds of landforms ranging from level plains to hummocky and rolling terrain of up to 50 m local relief. The lithology of glacial drift is generally characterized by the presence of calcium and magnesium carbonates incorporated from Paleozoic limestones. In the area of Chernozemic soils in Alberta, the carbonate contents of glacial till parent materials ranges from 6-16% $CaCO_3$ equivalent (St. Arnaud 1976). Chemical weathering releases calcium and, to a lesser extent, magnesium which play a major role in base element cycling of Chernozemic soils.

The predominant parent material of Chernozemic soils in Alberta is glacial till. Glacial till may occur in hummocky or rolling morainal deposits or in relatively flat terrain known as ground moraine or glacial till plains. Other common parent materials of Chernozemic soils are glaciolacustrine, glaciofluvial, and eolian deposits.

Chernozemic soil formation is the result of two major processes, namely humus formation, a product of the "biocycle", and the redistribution of bases, a consequence of the hydrological cycle (Pawluk 1983).

Humus formation begins with the growth of mixed herbaceous steppe vegetation. Organic matter reserves develop through release of exudates by deep, extensive root systems and by the decomposition of roots, leaves, and stems which die in late summer and autumn. Grasslands may contribute up to 50,000 kg ha^{-1} of organic material annually, half of which is from the roots (Pawluk 1983).

Organic matter degradation and humus formation follow a general ecological pathway involving a succession of microorganisms and of large and small fauna. Chemical energy of the decomposing material is progressively depleted. Simple organic constituents (sugars, amino acids, organic acids) as well as complex organic compounds (starches, celluloses, hemicellulose, lipids, proteins) are rapidly broken down. Lignins and lignoproteins can only be broken down by a few organisms and therefore tend to accumulate (Paul 1969). As the organic matter is degraded the C:N ratio narrows. The result of these activities is humus, partially a product of synthesis from various organisms and partially recalcitrant remains of original plant material substrates (Pawluk 1983).

The structure of humus is aromatic with simpler aliphatic groups attached. It is very stable with mean residence times ranging from 1000 to 1500 years. Humus becomes even more resistant in the presence of 2:1 clay minerals with which it forms complexes by means of various bonding mechanisms. Humic materials can completely engulf clay particles and thereby become further protected from decomposition.

The hydrological cycle is the other predominant factor involved in Chernozemic soil development. Limited water movement and leaching occur in these soils due to low rainfall. Downward clay movement is limited. Carbonates accumulate in C and lower B horizons due to high evapotranspiration rates while drainage is sufficient to keep the groundwater low enough to prevent the rise of sodium salts to the surface by capillary forces (Pawluk 1983). Primary minerals slowly weather to secondary minerals in the A and B horizons but little translocation occurs.

Variants of Chernozemic soils, which are characterized by processes and properties of other soil orders, are also recognized. These include soils with horizons of clay enrichment, calcium carbonate or salt enrichment, leaching, and others. Further information about genesis of Chernozemic soils can be found in Buol et al. (1980) and Fenton (1983).

4.5.4 Mineralogy and Geochemistry

Clay mineralogy of Chernozemic soils is dominated by smectites. Major quantities of illite and minor quantities of kaolinite and chlorite also occur. Clay minerals in these soils have undergone little weathering and redistribution except for some illitization of montmorillonite in the A-horizon (Dudas and Pawluk 1969/1970). Little variation in clay mineral composition was found in a study of 35 profiles of Chernozemic soils in Alberta (Kodama 1979).

Chernozemic soil mineralogical composition is similar to that of the underlying parent material. Tills in the region of Chernozemic soils contain 30-60% smectites and 15-30% illite in the clay fraction. The fine sand fraction of tills contains 6-8% potassium feldspar in most regions; significant areas of 8-10% and small areas of 4-6% also occur. Soda-calcic feldspars are variable over the region, ranging from 9-23% (Dudas 1968; Pawluk and Bayrock 1969).

The geochemical properties of Chernozemic soils are also similar to those of the till and other glacial sediments in which they develop. Areas of high calcium oxide in southern and central Alberta coincide with Chernozemic soil regions. In the south, CaO ranges from 6-10% (11-18% $CaCO_3$), while in the south central area it ranges from 3-6% (5-11% $CaCO_3$). Ranges in the contents of other elements are 2-3% iron, 0.025-0.045% manganese, 15-30 mg kg^{-1} copper, 40-90 mg kg^{-1} zinc, up to 2 mg kg^{-1} molybdenum, 4-9 (mainly 6-7) mg kg^{-1} cobalt, and 15-30 mg kg^{-1} boron (Pawluk and Bayrock 1969).

Soluble salt content in tills is variable, ranging from about 5-50 cmol(+)kg^{-1} (Pawluk and Bayrock 1969). The highest concentrations are in the southeast corner of the province and in a band running from the Vegreville area to the Stettler area. This distribution closely corresponds to that of Solonetzic soils. Sodium sulphate is the dominant salt. Chernozemic soils, by definition, are depleted of easily soluble materials in their sola and soluble salt concentrations of tills do not necessarily represent the concentrations found in their subsoils. Within areas of Chernozemic soils, however, saline and alkaline Gleysols, and Solonetzic soils may be found.

Chernozemic soils in till and other glacial deposits develop under conditions of abundant supply of bases from carbonates or weatherable silicate minerals. The high contents of clay minerals in these materials, particularly the 2:1 phyllosilicates characterized by high surface area and high charge density, have a stabilizing effect on soil humus brought about by the formation of clay-organic complexes. Large polymerized humic molecules may completely envelope clay particles and the complexation tends to protect the organic matter from decomposition. The typical granular structure of chernozemic A horizons is at least partly due to this stabilization effect through formation of organo-clay complexes (Pawluk 1983).

The other types of glacial deposits, namely glaciolacustrine, glaciofluvial and eolian materials, differ from till in particle size distribution and mineralogy. The minor elements (Fe, B, Co, Cu, Zn, and Mo) present in Alberta tills are principally associated with the clay-size fraction. Glaciolacustrine deposits are composed largely of silt and clay (Gravenor and Bayrock 1961) and levels of minor elements would thus be expected to be higher than in tills. Glaciofluvial and eolian deposits, on the other hand, consist largely of sand and gravel and are thus very low in levels of minor elements. Carbonate and salt contents of these deposits are similar to those of tills.

4.5.5 Biogeochemistry

Most Chernozemic soils in Alberta are used for agricultural production in systems ranging from intensively managed ones such as vegetable production under irrigation to minimally managed ones such as grazing on native grasslands. A diagramatic representation of nutrient cycling applicable to arable, livestock, and mixed farming systems is presented in Figure 4. It consists of three main compartments, plant, livestock, and soil, of which the latter is subdivided into available, organic, and mineral pools. Various fluxes describe its inputs, outputs, and transfers within the system. Agro-ecosystems from various countries have been analysed through application of this model. Nitrogen is the most characteristic nutrient element differentiating agricultural practices. Nitrogen outputs from soils have been found to range from 0.4 to 20 kg N ha^{-1} for extensive livestock and arable systems, while up to 113 kg N ha^{-1} has been reported to be lost from mixed farming systems (Frissel 1978). Detailed data for agro-ecosystems in Alberta are not available. However, it has been estimated that annual N losses from all the prairie provinces total about 1 million tonnes, or an average of 20-25 kg N ha^{-1} (Laverty et al. 1976). This figure represents about three times the fertilizer input to the soil N resource; there is, therefore, a tremendous yearly loss of native N from agro-ecosystems, although there is also some replishment by microbial N fixation and by lightning. Other aspects of N and of other elements are discussed below.

Organic matter contents of Chernozemic soils increase from the Brown to the Black soil zone with few exceptions. In general, Black Chernozemic soils contain the highest amounts of organic matter ranging from about 4% to over 7% total organic carbon in the Ah horizon. Dark Brown soils follow with 3% to over 4%, and Brown soils have approximately 1.6% to 3% total organic carbon in the Ah horizons. The thin Black and Dark Gray Chernozems average approximately 5% total organic carbon.

Cultivation of prairie soils has resulted in loss of an estimated 35-50% of organic matter (McGill et al. 1981b). The losses within various soil great groups are

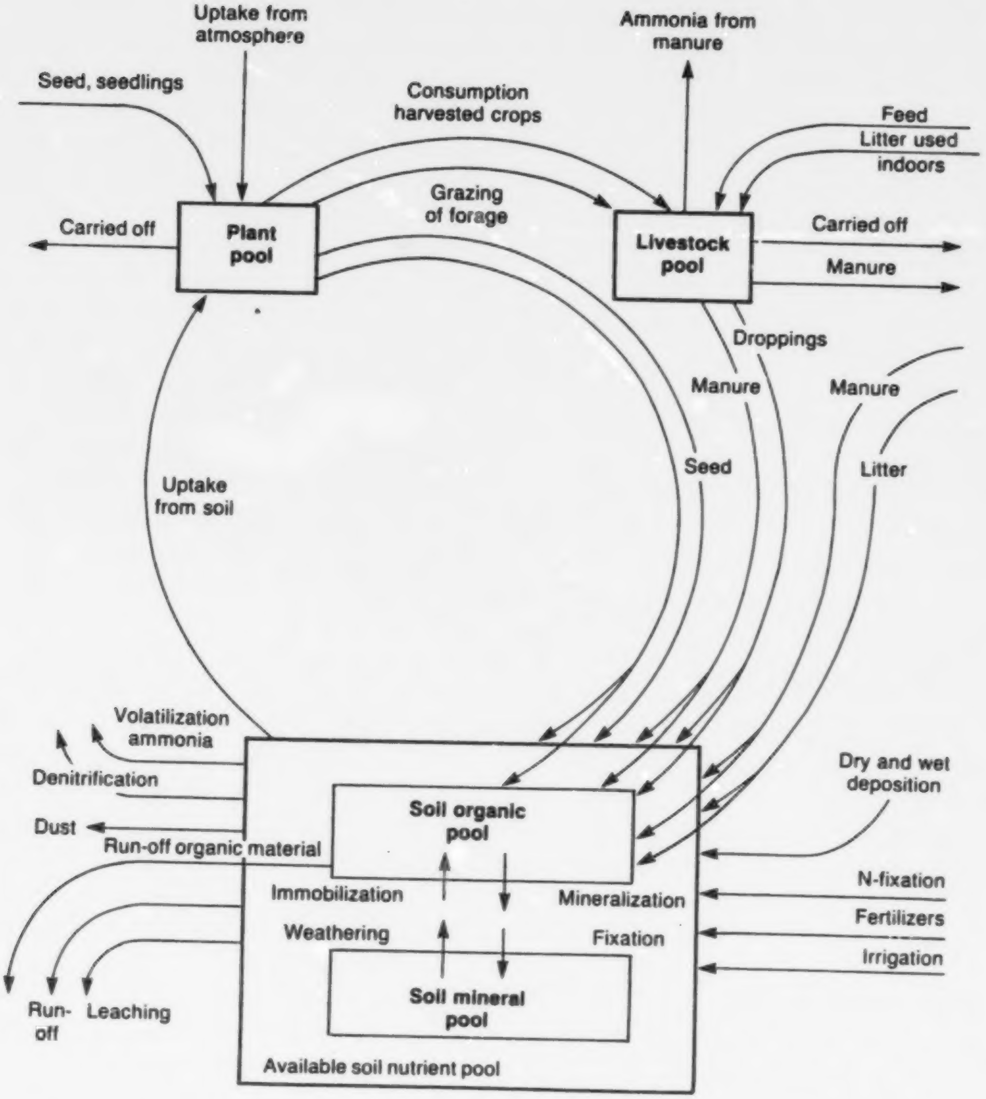

Uptake from atmosphere
Ammonia from manure
Seed, seedlings
Consumption harvested crops
Feed
Litter used indoors
Grazing of forage
Carried off
Plant pool
Livestock pool
Carried off
Manure
Droppings
Manure
Manure
Seed
Litter
Uptake from soil
Volatilization ammonia
Denitrification
Dust
Run-off organic material
Soil organic pool
Dry and wet deposition
N-fixation
Immobilization
Mineralization
Fertilizers
Weathering
Fixation
Irrigation
Soil mineral pool
Run-off
Leaching
Available soil nutrient pool

Figure 4. Diagram of an agro-ecosystem showing functional components and nutrient transfers (Source: Frissel 1978).

as follows: Brown - 38%; Dark Brown - 42%; Black - 47%; Dark Gray - 40%; and Gray Luvisol - 35%. Cultivation has a tremendous impact on the organic matter characteristics of soils. A wheat fallow system on Brown, Dark Brown, and Black Chernozemic soils decreased the organic carbon content by as much as 60% and the total nitrogen content by as much as 46% (Dormaar 1979). Humic acid/fulvic acid ratios decreased little for semiarid soils after cultivation, and decreased up to 38% in Black soils. In more recent work, Reinl (1984) found that concentrations of organic carbon in cultivated A horizons decreased by 52%, 42%, 40%, 13%, 75%, and 64% in Brown, Dark Brown, Black, Dark Gray, Gray Luvisol, and Peace River sampling zones, respectively. Mass losses in soil profiles were 36%, 25%, 21%, 22%, 39%, and 28%, respectively in these sampling zones. The loss of organic matter has resulted in reduction of nutrient supplying ability and in deterioration of physical properties. As a result, more fertilizers are required and erosion problems may develop (McGill et al. 1981b). Maintaining organic matter levels in soils has become a concern and as a result cropping systems and cultivation practices are undergoing changes to solve the problem. Reinl (1984) noted that net gains in organic carbon occurred within some farming units in which organic matter replenishment operations were carried out.

Major nutrients for plant growth are nitrogen, phosphorus, potassium, and sulphur. Nitrogen and phosphorus are the two most common limiting nutrients in Alberta. Information on nitrogen levels in the soils of Alberta is not readily available since mineral nitrogen concentration fluctuates dramatically within and among years due to climate and management practices. Phosphorus is deficient in about 93% of the agricultural lands, with 41% being severely deficient. Most of the severely deficient phosphorus soils are in the south but deficient areas also occur in the central and Peace River regions (Kryzanowski and Laverty 1985). Potential potassium deficiencies have been found in only 17% of the agricultural land. The range between deficient and sufficient is 125 to 150 mg kg^{-1} depending on the crop. There may be 2.8 million hectares deficient in potassium but only 0.6 million hectares of these are severely deficient and limiting to plant growth. These severely deficient areas are concentrated in the Gray and Dark Gray soil zones in east central Alberta. Other smaller potassium deficient areas occur southwest of Edmonton and in the north Peace River region. Southern Alberta has almost no deficiencies in potassium (Kryzanowski and Laverty 1985). Area estimates for sulphur deficiencies range from 3 to 30%. Sulphur becomes deficient below 3.0 mg kg^{-1} sulphate sulphur in the 0-15 cm depth for most crops. Southeastern Alberta has large quantities of sulphate salts but deficiencies can occur here, as the salts are fairly deep in the profile (Penney and Carson 1977). Northeastern Alberta probably has the most sulphur-deficient soils, especially where grass and grass-legume crops have been grown. A detailed area estimate summary of phosphorus, potassium, and sulphur levels in specific regions and municipalities has been published by Alberta Agriculture (1985).

Micronutrients are rarely deficient in Alberta. They include the elements B, Cl, Cu, Fe, Mn, Mo, and Zn (Alberta Agriculture 1983). Boron contents in tills, as noted above, are generally between 15 and 30 mg kg^{-1}, but some soils in Alberta have only about 0.5 mg kg^{-1} extractable B in Ap horizons. However, only corn has shown deficiencies (Alberta Agriculture 1983). Copper tends to range within 15-30 mg kg^{-1} in the till underlying Chernozemics (Pawluk and Bayrock 1969), while 16-29 mg kg^{-1} were found in the solum of soils under native vegetation (Dudas and Pawluk 1980) and 3-6 mg kg^{-1} in Ap horizons of cultivated soils (Dudas and Pawluk 1977). Distribution of Cu throughout the profile was fairly uniform with some enrichment in surface horizons; this was highly correlated with clay content (Dudas and Pawluk 1980). Iron was found in quantities of 2-3% in tills under Chernozemic soils (Pawluk and Bayrock 1969). McKeague et al. (1979) reported values of 1.8-2.0% in B and C horizons of one Black Chernozemic. Manganese was reported at 0.025-0.040% in Alberta tills. McKeague et al. (1979) reported 250-330 mg kg^{-1} in B and C horizons of a Black Chernozem, while Dudas and Pawluk (1977) reported 230-270 mg kg^{-1} for the Ap horizons of several agricultural soils. Molybdenum contents of Alberta tills range from 0-2 mg kg^{-1} in the south and south central areas (Pawluk and Bayrock 1969). Zinc ranges from 50-90 mg kg^{-1} in tills (Pawluk and Bayrock 1969) and 48-105 mg kg^{-1} in soils under native vegetation (Dudas and Pawluk 1980). Dudas and Pawluk (1977) found 5-15 mg kg^{-1} extractable Zn in Ap horizons. They also found Ah horizons were noticeably enriched compared to C horizons. In irrigated areas, Zn tested low but no deficiencies were found (Alberta Agriculture 1983). Cobalt concentrations in till range from 5-9 mg kg^{-1} (Pawluk and Bayrock 1969), while soils tend to have 6.4-13 mg kg^{-1} (Dudas and Pawluk 1980) under native vegetation. Dudas and Pawluk (1977) also found that extractable Co ranged from 1.4 to 4.0 mg kg^{-1} in Ap horizons of various Chernozemics. They also found B horizons to be enriched with this element, probably as a result of translocation from the A horizons. Little information is available about V and Si levels in Alberta's Chernozemic soils.

Levels of other microelements or heavy metals (trace elements) such as Hg, Cd, Ni, Sr, Pb, and As in several Chernozemic soils in Alberta have been reported by Dudas and Pawluk (1976, 1977, 1980). McKeague et al. (1979) have also collected data for these as well as for Ti, Cr, and Se for one Orthic Black Chernozemic series (Maleb). Total Hg content ranges from 17 to 71 $\mu g\ kg^{-1}$ (Dudas and Pawluk 1976) with 0.56 to 27 $\mu g\ kg^{-1}$ of this being HCl extractable. Ah and Ap horizons tend to contain 20-35 $\mu g\ kg^{-1}$ of Hg and C horizons an average of 44 $\mu g\ kg^{-1}$ (Dudas and Pawluk 1976). Depleted levels of Hg in Ah, AB, and some Bn horizons may be due to translocation to C horizons (Dudas and Pawluk 1976). Cadmium levels ranged from 0.15 to 0.53 mg kg^{-1} in Alberta's Chernozemics. Dudas and Pawluk (1980) found enriched levels in surface horizons as compared to C horizons. Nickel in soils was found to range from 5.0 to 7.0 mg kg^{-1}, but should probably be much higher because crustal abundance is reported to be 75 mg kg^{-1} (Dudas and Pawluk 1977). They suggested that eluviation is the cause of decreased levels in the soil profile. Strontium levels range from 10-30 mg kg^{-1} (Dudas and Pawluk 1977) in Chernozemic soils. This element has a significant positive correlation with exchangeable Ca and extractable Al (Dudas and Pawluk 1977). Lead was reported to range from 12-21 mg kg^{-1} by Dudas and Pawluk (1980). They also found Pb to be the most uniformly distributed element in the soil profile (i.e., no apparent redistribution within the profile). Arsenic was found to be slightly depleted from Ah horizons and ranged from 3.5 - 6.9 mg kg^{-1} (Dudas and Pawluk 1980). Little information is available on Ti, Cr, and Se levels in Alberta soils. McKeague et al.(1979) reported 0.19-0.27% for Ti, 26-59 mg kg^{-1} for Cr, and 0.32-0.52 mg kg^{-1} for Se in an Orthic Black Chernozemic soil. Levels of heavy metals and other microelements were low and in amounts normal for uncontaminated soils. Distribution throughout the profile is dependent on pedogenesis, parent material, drainage and groundwater. Anthropogenic sources of heavy metal contamination have apparently not had an effect as yet on the agricultural soils of Alberta (Dudas and Pawluk 1977).

4.5.6 Soil Reaction

The pH of cultivated soils in the prairie provinces is generally in the alkaline or neutral range. However, soil acidity is a problem, particularly in Luvisolic soils such as those of the Peace River region. In the Brown and Dark Brown soil zones, Solonetzic soils are commonly acidic (Penney et al. 1977). Distributions of pH ranges as summarized from the report of Holowaychuk and Fessenden (1986) are given in Table 6.

Some soils with pH values less than 6.1 in the Ap horizons in the Chernozemic order are found in the Thin Black and Dark Brown soils north of the Bow River (Penney et al. 1977). Further information on location and extent of acid soils in this order are discussed by Holowaychuk and Fessenden (1986) and in Section 5. Further information is also available from a pH distribution map of agricultural areas of the province as derived from data obtained from samples submitted to the Alberta Soil and Feed Testing Laboratory (Alberta Agriculture 1971; 1974-1984 map in prep., L. Krzanowski, Alberta Agriculture, pers. comm.).

4.5.7 Ion Exchange Properties

Ion exchange is a reversible process by which cations and anions are exchanged between solid and liquid phases or two solid phases which are in contact with one another (Tisdale and Nelson 1975). The major cations in soils are: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, and $Al^{3+}(H^{+})$ (Bohn et al. 1979). In productive agricultural soils such as Chernozemic soils of Alberta the amounts of the major exchangeable ions are: $Ca^{2+} > Mg^{2+} > K^{+} = Na^{+}$. Cation exchange capacity (CEC) in Alberta soils has been recorded in tabular form by Holowaychuk and Fessenden (1986) and is summarized in Table 7.

More specific information on CEC values in western Canadian Chernozemics are available in soil survey reports and various papers: for example, Rice et al. (1959), Bowser et al. (1962), St. Arnaud and Mortland (1963), and Dudas and Pawluk (1969/1970).

The dominant cation in Chernozemic soils is calcium. It generally accounts for 50-80% of the exchangeable cations. Magnesium may occupy 10-30% of the exchange sites, potassium 1-10%, hydrogen up to 30%, and sodium less than 15% but usually only 1-5% (Rice et al. 1959; Bowser et al. 1962).

The major anions are NO_3^-, SO_4^{2-}, Cl^-, HCO_3^-, and CO_3^{2-}. Other common soil anions are HPO_4^{2-}, $H_2PO_4^-$, OH^-, and F^-. Micro- nutrients and heavy metals also exist as anions and include $H_2BO_3^-$, MoO_4^{2-}, CrO_4^{2-}, and $HAsO_4^-$ (Bohn et al. 1979). Sulphate is the principle anion and is usually highest in the C horizon in the Chernozemic order (Bowser et al. 1962). Anions are retained by soils through various reactions which are divided into two groups, namely nonspecific and specific adsorption or chemi-sorption (Section 3.3). Anion exchange capacities in all of the soil orders are considerably lower than cation exchange values and are seldom recorded.

Table 6. Reaction (pH) of Chernozemic soils.[1]

Great Group	Layer	$pH(H_2O)$ - Range	Most Common pH Range
Brown	Surface[2]	6.1 - 7.7	6.6 - 7.7
	Subsoil	6.1 - 7.7	7.3 - 7.7
Dark Brown	Surface	6.1 - 7.3	6.1 - 7.3
	Subsoil	6.6 - 7.7	6.6 - 7.7
Black	Surface	5.6 - 7.8+	6.1 - 7.3
	Subsoil	5.6 - 7.8+	6.1 - 7.3
Dark Gray	Surface	5.6 - 7.3	5.6 - 6.5
	Subsoil	5.6 - 7.3	6.1 - 7.3

[1] Adapted from the original tables in Holowaychuk and Fessenden (1986).

[2] Surface is defined as the 0-20 cm layer; subsoil thickness is variable and is defined as the material below the surface to the bottom of the B horizon.

Table 7. Cation exchange properties in the great groups of the Chernozemic order.[1,2]

Great Group	CEC Range (cmol(+)kg^{-1})	Most Common CEC Range (cmol(+)kg^{-1})	Exchangeable Bases Range (cmol(+)kg^{-1})	Most Common Exch. Bases Range (cmol(+)kg^{-1})	Base Sat. (%) Range
Brown					
(Surface)	3-25+	15-25	3-25+	6-25	50-100
(Subsoil)	3-30+	15-25	3-30	15-25	100
Dark Brown					
(Surface)	3-35+	20-30	3-35	12-28	70-100
(Subsoil)	2-30	15-30	2-30	15-30	100
Black					
(Surface)	6-45+	20-35	6-45+	15-35	70-100
(Subsoil)	<5-40+	15-30	<5-40+	15-25	80-100
Dark Gray					
(Surface)	20-40	25-35	18-35	22-35	80-90+
(Subsoil)	15-35	18-25	13-32	13-22	80-100

[1] Adapted from the original table in Holowaychuk (1986)

[2] Abbreviations: CEC = cation exchange capacity; Exch. = exchangeable; Sat. = saturation

4.5.8 Major Series

The Canadian system of soil taxonomy is a hierarchical scheme in which soil orders are progressively subdivided into great groups, subgroups, families, and series. The soil series is the basic unit of soil classification and consists of soils that are essentially alike in all major profile characteristics except the texture of the surface. Soil series of significant areal extent, arbitrarily defined as those of 100 or more mapped sections, are listed in Table 8. Data for this and similar tables for the other soil orders were obtained from SIDMAP, a computer soil data base for Alberta (Patterson and Peterson 1984). Only data for soils mapped at reconnaissance or higher levels of inventory reside in SIDMAP. Thus, most of northern Alberta, which has been mapped at exploratory levels only, is not represented in the SIDMAP data base. The mapped areas generally correspond to the white and yellow land use areas of the province (see Thompson (1981) for land use area map).

There are a large number of soil series and complexes which have been mapped within each of the soils orders in Alberta. Further information about these can be obtained from soil survey reports and from the Agriculture Canada Pedology Unit (W. Pettapiece, pers. comm.). Descriptions of some pedons representative of the Chernozemic order are provided in Tables 9, 10, 11, 12, and 13. The descriptions serve to illustrate the properties of Chernezomic soils through selection of some typical profiles and also to provide data for calculations of acid deposition impacts in Section 5.

4.5.9 Land Use

A large proportion of Chernozemic soils of Alberta are cultivated, but large areas of unimproved rangeland remain in the Brown and Dark Brown soil zones. Improvement Districts 1 and 3 are dominated by Brown Chernozemics and are 70-100% noncultivated. The rest of the counties and municipalities contain no more than 40% unimproved land with another 10-20% taken up by improved pasture land. The remaining area is cropped. According to the Alberta 1981 Census (Alberta Agriculture 1982), spring wheat is the dominant crop on Brown and Dark Brown Chernozemics. Barley and oats are the next most abundant. In the Black and Dark Gray Chernozemic soil zones, barley is the more common crop followed by wheat and oats. Hay crops are usually an alfalfa - grass mixture.

Many different crop rotations are used throughout the Chernozemic soil area. Brown soils are generally managed by a two year wheat-fallow rotation. Irrigated areas are continuously cropped. Dark Brown Chernozemic areas are usually farmed with 3-5 year rotations, which include one year of fallow. Common rotations are wheat-wheat-fallow, wheat-wheat-barley-fallow, canola-wheat-wheat-fallow, canola-wheat-wheat-barley-fallow, and canola-wheat-barley-barley-fallow. Black and Dark Gray Chernozemic regions are farmed using 4-5 year rotations involving wheat, barley, canola and oats or 5-7 year rotations involving hay and barley (personal communication, Assessment Standards Branch, Alberta Municipal Affairs 1985).

Rangeland and improved pasture take up a large part of the Chernozemic soils. Information and maps of the range vegetation zones in Alberta are available in the Farm Management Data Manual (Alberta Agriculture 1981). Brown soils of Zone 1 are dominated by needle and thread (Stipa comata) and blue grama (Bouteloua gracilis) species. Dark Brown soils predominantly have needle and thread, blue grama, and a western wheatgrass

Table 8. Major soil series of the Chernozemic order in the white and yellow land use areas.[1]

			Mapped Area	
Soil Subgroup	Textural Family	Series	Sections	km^2
Orthic Brown	fine-loamy	Maleb	2929	7587
		Foremost	1582	4097
		Chin	1328	3440
	coarse-loamy	Bingville	926	2398
	sandy	Cavendish	934	2419
Calcareous Brown	clayey	Acadia Valley	101	262
Solonetzic Brown	fine-loamy	Cecil	418	1083
Orthic Dark Brown	fine-loamy	Hughenden	3070	7951
		Lethbridge	2413	6250
	coarse-loamy	Metisko	1095	2836
	sandy	Wainwright	928	2404
	clayey	Drumheller	609	1577
	loamy-skeletal	Scollard	139	360
Rego Dark Brown	fine-loamy	Altario	130	337
	sandy	Houcher	189	490
Orthic Black	fine-loamy	Elnora	2401	6219
		Beazer	1584	4103
		Beaver Hills	1345	3484
		Airdrie	1107	2867
		Dunvargon	1002	2595
	coarse-loamy	Peace Hills	927	2401
	sandy	Morningside	309	800
	clayey	Pincher	164	425
Rego Black	fine-clayey	Parsons	138	357
Eluviated Black	fine-loamy	Angus Ridge	1854	4802
		Ponoka	1049	2717
	clayey	Malmo	509	1318
Solonetzic Black	fine-loamy	Heisler	270	699
Gleyed Black	fine-loamy	High Prairie	382	989

continued...

Table 8 (Concluded).

Soil Subgroup	Textural Family	Series	Mapped Area Sections	km²
Orthic Dark Gray	fine-loamy	Falun	804	2082
		Mico	228	591
	coarse-loamy	Redwater	122	316
	sandy	Helliwell	100	259
Solonetzic Dark Gray	clayey	Albright	690	1787
Other Subgroups[2]	-	-	-	-

[1] Adapted from the original tables in SIDMAP (Patterson and Peterson 1984).

[2] Although mapped, total series area is less than 100 sections.

Table 9. Description of an Orthic Brown Chernozemic - Cavendish series.[1,2]
(SE14-21-17-W4; rapidly drained; glaciofluvial and eolian; sandy)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
Ah	0-23	dark brown (10YR 3/3m)	loamy sand	single grain	very friable	plentiful	clear, smooth
Bm	23-61	dark brown to brown (10YR 4/3m)	sand	single grain	very friable	plentiful	gradual, wavy
C	61-76+	dark yellowish brown to yellowish brown (10YR 4/4-5/4m)	sand	single grain	loose	few	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
Ah	6.5	-	0.1	0.8	8	0.0	0.7	6.2	0.2	8.1	88	-	87	5	8
Bm	6.9	-	-	0.3	-	0.1	0.7	5.8	0.0	6.3	100	-	91	2	7
C	7.3	-	-	-	-	-	-	-	-	-	-	0.0	92	2	6

[1] Adapted from the original table in Kjearsgaard et al. (1983)
[2] Abbreviations and symbols: colour symbols according to Munsell soil colour charts (Soil Survey Staff 1975); m = moist; d = dry; Sat. = saturation; Equiv. = equivalent.

Table 10. Description of an Orthic Dark Brown Chernozemic - Cradduck series.[1,2]
(NW15-4-18-W4; well drained; morainal; fine-loamy)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
Ap	0-17	very dark grayish brown (10YR 3/2m)	loam	moderate, fine subangular blocky	very friable	-	clear, smooth
Bm	17-31	dark brown (7.5YR 3/2m)	clay loam	moderate, fine to medium prismatic	friable	-	clear, wavy
Cca	31-58	grayish brown (2.5Y 5/3m)	clay loam	massive	very friable	-	gradual, wavy
Ck	58-100+	dark grayish brown (2.5Y 4/2m)	clay loam	massive	very friable	-	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
Ap	6.8	6.5	0.20	2.32	12	0.1	2.0	12.7	2.4	22.3	77	-	38	36	26
Bm	6.8	6.4	-	1.06	-	0.1	1.1	14.7	3.3	25.3	76	-	32	36	32
Cca	7.4	7.2	-	-	-	0.1	0.3	38.3	6.1	19.7	100	17.5	28	30	32
Ck	7.6	7.5	-	-	-	-	-	-	-	14.4	-	14.4	25	40	35

[1] Adapted from the original table in Kjearsgaard et al. (1984)
[2] See Table 9 for explanation of abbreviations and symbols.

Table 11. Description of an Orthic Black Chernozemic - Peace Hills series.[1,2] (SW10-55-15-W4; well drained; glaciofluvial; sandy)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
Drift	42-0	very dark gray (10YR 3/1m)	sand	weak, medium granular	friable	common	abrupt, smooth
Ah	0-25	very dark gray (10YR 3/1m)	loamy sand	moderate, medium granular	friable	common	clear, wavy
AB1	25-35	dark brown (7.5YR 3/2m)	loamy sand	weak, medium granular	friable	few	gradual, wavy
AB2	35-52	brown to dark brown (7.5YR 4/2m)	loamy sand to sand	weak, medium granular	friable	few vertical	clear, wavy
Bm	52-88	yellowish brown (10YR 5/4m)	sand	single grain	loose	few	clear, wavy
C	88+	brown (10YR 5/3m)	sand	single grain	loose	few	

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
Drift	6.7	-	0.16	2.40	15	0.0	0.2	5.2	0.7	10.0	61	-	89	7	4
Ah	6.5	-	0.13	2.15	17	0.0	0.3	4.4	0.7	9.2	59	-	85	9	6
AB1	6.6	-	0.05	0.90	18	0.1	0.4	2.0	0.6	5.8	53	-	85	10	5
AB2	6.8	-	0.02	0.75	38	0.0	0.3	1.4	0.4	4.7	45	-	87	8	5
Bm	6.8	-	0.02	0.40	20	0.2	0.3	2.2	0.5	5.7	56	-	90	5	5
C	6.7	-	-	-	-	0.0	0.2	2.0	0.5	5.7	47	-	88	6	6

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[1] Adapted from the original table in Macyk et al. (1985)

[2] See Table 9 for explanation of abbreviations and symbols.

Table 12. Description of a Calcareous Black Chernozemic - Lloyd Lake associate.[1,2]
(Calgary vicinity; well drained; glaciolacustrine; fine-loamy)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
Ahk1	0-15	black (10YR 2/1d)	clay loam	moderate, medium and coarse granular	slightly hard	-	clear, smooth
Ahk2	15-30	very dark gray (10YR 3/1m)	clay loam	moderate, medium to coarse prismatic	very friable	-	gradual, smooth
Bmk	30-36	very dark grayish brown (10YR 3/2m)	loam	moderate, medium to coarse prismatic	very friable	-	clear, wavy
Cca	36-50	dark grayish brown (10YR 4/2m)	silt loam	amorphous	very friable	-	gradual, smooth
Ck	50+	pale brown (10YR 6/3m)	silt loam	amorphous	very friable	-	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
Ahk1	7.8	7.4	0.44	3.85	9	-	-	-	-	-	-	3.0	20	49	31
Ahk2	7.9	7.4	0.33	2.93	9	-	-	-	-	-	-	6.8	26	46	28
Bmk	7.9	7.6	0.21	3.02	14	-	-	-	-	-	-	23.1	34	41	25
Cca	8.4	7.8	-	-	-	-	-	-	-	-	-	38.0	16	57	27
Ck	8.7	8.1	-	-	-	-	-	-	-	-	-	35.9	11	71	18

[1] Adapted from the original table in MacMillan (1985)

[2] See Table 9 for explanation of abbreviations and symbols.

Table 13. Description of an Orthic Dark Gray Chernozemic - Redwater series.[1,2]
(Ewand vicinity; undulating; well drained; glaciofluvial and eolian; sandy)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
Ahe1	0-30	dark grayish brown (10YR 4/2m)	loamy sand	weak, fine granular	very friable	-	gradual, wavy
Ahe2	30-46	grayish brown (10YR 5/2m)	loamy sand	very weak, medium platy	loose	-	clear, wavy
Bm	46-71	yellowish brown (10YR 5/4m)	sandy loam	weak, medium prismatic	friable	-	gradual, wavy
BC	71-112	brown (10YR 5/3m)	loamy sand	single grain	loose	-	gradual, wavy
Ck	112+	brown to grayish brown (10YR 5/3-5/2m)	sand	single grain	loose	-	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations ($cmol(+)kg^{-1}$)				Total CEC ($cmol(+)kg^{-1}$)	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
Ahe1	6.7	-	0.10	1.09	11	0.1	0.2	7.5	0.9	9.8	89	-	77	17	6
Ahe2	6.8	-	0.04	0.38	9	0.1	0.2	4.4	0.7	5.9	91	-	79	15	6
Bm	6.8	-	0.03	-	-	0.1	0.1	4.6	0.8	5.8	97	-	-	-	-
BC	6.5	-	0.03	0.22	7	0.1	0.1	5.0	0.9	6.4	95	-	-	-	-
Ck	7.8	-	-	-	-	-	-	-	-	-	-	1.9	89	8	3

[1] Adapted from the original table in Kjearsgaard (1972)

[2] See Table 9 for explanation of abbreviations and symbols.

(Agropyron smithii) (Zone 2) with areas of porcupine grass (Stipa spartea var. curteseta) and wheatgrass (Zone 3), and parkland (Zone 5). Black and Dark Gray Chernozemics occur in Zones 3, 4 (rough fescue, Festuca scabrella), 5, and 6 (Brush pastures).

4.6 SOLONETZIC ORDER

4.6.1 General Description

Solonetzic soils are distinguishable from other soils by the high proportion of exchangeable sodium or sodium-plus-magnesium salts in the B horizon. This horizon is hard when dry, and sticky and almost impermeable when wet. Solonetzic B horizons are prismatic or columnar in macrostructure and blocky with dark coatings in mesostructure (Expert Committee on Soil Survey 1978).

There are three great groups in the Solonetzic order which are separated on the basis of Ae horizon thickness and degree of breakdown in the B horizon. The great groups are: Solonetz, which has no continuous Ae at least 2 cm thick and has Bn or Bnt horizons; Solodized Solonetz, which has an Ae horizon at least 2 cm thick and an intact columnar Bnt or Bn horizon; and Solod, which has an Ae at least 2 cm thick and a distinct AB or BA horizon (disintegrating Bnt) (Expert Committee on Soil Survey 1978).

4.6.2 Distribution and Extent

Solonetzic soils occupy about 30% of Alberta's arable land. The largest area of Solonetzic soils occurs in the low relief plain running north-south through central Alberta from Vegreville to Brooks. These soils also occur in the Peace River region and near Leduc and Westlock (Hardy 1984). The relative extent of each of the great groups varies across the province. Solodized Solonetz soils are most common in central and southern Alberta; Solods are most common in the Peace River region (Hardy 1984).

4.6.3 Genesis

The basic concept of Solonetzic soil development consists of salinization followed by solonization (desalinization and alkalization) and solodization (Pawluk 1982). Salinization includes processes whereby soluble salts accumulate at or near the soil surface. In western Canada, Solonetzic soil formation begins when a dominance of sodium salts is maintained at the soil surface or in the upper section of the soil profile by groundwater discharge. As groundwater flows downward from the water table (recharge) through the geological strata in its flow path, salts from the strata are dissolved and transported to the water table (discharge area). The water table is maintained at an equilibrium position by a balance between gains and losses from the groundwater regime and gains and losses from the unsaturated zone by evapotranspiration and precipitation (Pawluk 1982). Groundwater flow systems, which may be local, intermediate or regional in extent, are one of the most important factors of Solonetzic soil formation in Alberta. Of the three groundwater systems, regional systems are probably primarily responsible for most of the salt discharge and consequent Solonetzic soil formation in Alberta. Pawluk (1973) suggested that salt deposition in Alberta probably occurred immediately after the last glaciation and that salinization was probably most extensive in the Altithermal, but still continues to be a dynamic process in many areas of the province.

The next stage in Solonetzic soil genesis is solonization which includes the processes of desalinization and alkalinization. Desalinization occurred in the Great Plains as the climate changed and integrated drainage systems developed. During the Altithermal, high rates of evapotranspiration caused a salt flux to remain in the capillary fringe. Sodium ions were maintained by capillary flow through fine pores, while desalinization took place by downward gravitational flow through a large pore. Dispersion of soil colloids occurs when the total salt content is 0.10 - 0.15% or less and sodium ions occupy at least 10-15% of the exchange complex. Soil colloids in a dispersed state wash down readily to form an incipient clay pan. The salinization-desalinization process has to remain dynamic to counteract sodium displacement by calcium ions which exist in the layer or are introduced through biocycling. Sodium clays are also susceptible to hydrolysis during alkalization. Hydronium ions displace sodium ions, which in turn are displaced by aluminum hydroxy ions released during chemical weathering. If sodium and bicarbonate ions are in low concentration in the pore water, the sodium-saturated clay colloids remain dispersed and can continue to wash down to form the solonetzic B horizon (Pawluk 1982).

The final stage in Solonetzic genesis is solodization. After the B horizon becomes impermeable, the hydrology of the upper horizon is altered. Capillary flow is limited to the top of the B horizon and sodium ions can no longer get up into the A horizon to replenish it. Mild alkalinization occurs. Exchangeable sodium is displaced by aluminum hydroxy ions. Calcium and magnesium ions from weathering of soil minerals and biocycling then displace the aluminum. Movement of soluble constituents is lateral or into the large pore spaces. The result is a mildly weathered acidic A horizon and an alkaline solonetzic B. As long as the capillary fringe maintains continuity with its upper boundary, the B horizon will remain intact and dispersed (Pawluk 1982). As soon as this continuity is broken down, leaching of the salic layer occurs and solonetzic processes are no longer active.

The formation of Solonetzic soils is largely dependant upon groundwater conditions. Maintaining the water table in the capillary fringe of the soil profile allows for Solonetzic soils to remain in their steady state. B horizon degradation occurs if this condition is not met and the soil will evolve to other soil orders.

4.6.4 Mineralogy and Geochemistry

The mineralogy of Solonetzic soils is very similar to that of their parent materials. Over 50% of these soils in Alberta occur on glacial till. A weakly to moderately saline till derived from the Edmonton formation forms the parent material for many of these Solonetzic soils. This formation is from the Upper Cretaceous and consists of thin alternating beds of white and grey sandstones, silty sands, shales, black shales, and coal (Kunkle 1962, cited by Brunelle et al. 1976). Other parent materials and their extent under solonetzic soils are listed in the Table 14.

Distribution of clay sized minerals through soil profiles is largely dependent on pedogenesis. The dominant mineral in the total clay fraction is smectite. Brunelle (1969), Van Schaik and Pawluk (1973), and Brunelle et al. (1976) found that smectite was the dominant clay mineral in all horizons of the Brown and Eroded Brown Solonetz on till, Brown and Eroded Brown Solods on till, Black Solonetz on lacustrine, and Black

Table 14. Hectares of Solonetzic order soils on different parent materials mapped up to 1973.[1]

	Soil Group				
	Gray	Black	Dark Brown	Brown	Totals
In Central and Southern Alberta					
Till	71,685	824,175	267,705	1,173,690	2,337,255
Alluvial-lacustrine	-	29,160	29,160	201,690	260,010
Aeolian	-	17,820	30,780	80,190	128,790
Lacustrine	37,665	171,720	32,400	33,615	234,900
Residual	11,340	143,775	125,550	36,855	317,520
Total	120,690	1,186,650	485,595	1,526,040	3,278,475
In the Peace River Area					
Till	176,580	-			176,580
Lacustro till	562,140	298,890			861,030
Lacustrine	109,755	382,320			492,075
Residual	12,150	45,765			57,915
Total	860,625	726,975			1,587,600
				Total for the province	4,866,075

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[1] Adapted from the original table in Peters (1973).

Solod on lacustrine that were studied. Illite is more abundant in Ae horizons of Brown Solods, probably due to preferential translocation of smectite over illite. The Bnt and C horizons had marked accumulation of smectite. It was also observed that the illite content in the clay fraction was greater in the illuvial horizon than in the C horizon. This was probably due to illitization. The unidentified portion was probably composed of chlorite, kaolinite, and amorphous material (Brunelle et al. 1976). Up to a quarter of the clay fraction in these horizons could be quartz.

The mineralogical composition and distribution of the fine sand size fraction is strongly dependent on parent material composition and weathering rates of the minerals themselves. The dominant mineral in the fine sand size fraction is quartz (Brunelle 1969; Van Schaik and Pawluk 1973; Brunelle et al. 1976). These researchers found soda-calcic feldspars in larger quantities than potassium feldspars in every horizon in every profile but weathering was greater in the soda-calcic feldspars (Brunelle 1969).

The geochemical properties of Solonetzic soils are also very similar to those of their parent materials. By comparing the soil map of Holowaychuk and Fessenden (1986) with the maps of glacial till composition by Pawluk and Bayrock (1969), estimates of total elemental content were made for the Solonetzic soil regions of the province as follows: calcium oxide, 2 to 8%; iron, 2.50 to 3.75%; zinc, 50 to 100 mg kg^{-1}; copper, 15 to 40 mg kg^{-1}; manganese, 0.020 to 0.040 mg kg^{-1}; molybdenum, 0 to 2 mg kg^{-1}; cobalt, 5 to 9 mg kg^{-1}; and boron, 20 to 55 mg kg^{-1}. Soluble salt content varied widely for the different regions. The south and south central regions ranged from 15 to 50 cmol kg^{-1}, the Peace River region ranged from 5 to 25 cmol kg^{-1}, and the north ranged from 0 to 10 cmol kg^{-1}. The principal salt is sodium sulphate in the south and south central regions although magnesium sulphate is also present in significant amounts (Pawluk and Bayrock 1969). The tills of the Peace River region contain large amounts of low to moderately soluble magnesium salts which generally remain in the the lower solum. Soluble salt contents of soil and till do not coincide with specific bedrock formations. Also, salt content shows no correlation with other chemical and mineralogical aspects of till, nor does it reflect the original composition of the till. Salt content is acquired after deposition through past and present groundwater discharge and climatic conditions.

4.6.5 Biogeochemistry

Soil organic matter contents of Solonetzic soils are similar to those of the soil orders surrounding them. Solonetzic soils within the Brown, Dark Brown, and Black Soil zones are similar to Chernozems in organic matter content of Ah and Ap horizons and Solonetzic soils in the Peace River regions contain organic matter in similar quantities to the surrounding Luvisols. Solonetzic soils are not classified on the basis of organic matter but rather on the basis of the diagnostic Bnt horizon, as indicated previously. Solonetzic soils can have Chernozemic A horizons as can Luvisols. Cultivation of Solonetzic soils has resulted in organic matter losses over time; the discussion for Chernozemic soils in Section 4.5.5 is applicable to Solonetzic soils as well. C/N ratios do not vary significantly among the great groups and average 11-12 in Ah, Ae, and Bt horizons (Bowser et al. 1962).

Major nutrients, micronutrients, and heavy metal contents in Solonetzic soils are also similar to those of the soil orders which surround them. The levels of nutrients and heavy metals in the Solonetzic soils of south and south central Alberta are similar to those of Chernozemic soils, and Solonetzic soils of the Peace River region are likewise similar to the Luvisolic soils surrounding them.

4.6.6 Soil Reaction

The plow layer of some Solonetzic soils can be very acidic while the subsoils are generally alkaline. Liming has been shown to increase crop yields substantially (Hoyt et al. 1981). Mixing of subsoil and topsoil by deep plowing has also been shown to be beneficial to crop growth and yields (Hermans 1979). A summary of pH ranges in Solonetzic soils is provided in Table 15.

Further information about pH of Solonetzic soils can be derived from the pH map of Alberta Agriculture (1971). A soil pH map has also been produced for the County of Paintearth which has a large area of Solonetzic soils (Wells 1985).

4.6.7. Ion Exchange

Ranges of cation exchange capacities, exchangeable bases, and base saturation percentages of Solonetzic soils, as derived from Holowaychuk and Fessenden (1986) are summarized in Table 16. Total exchange capacities in mineral soils are dependent on clay and organic matter content. CEC ranges consequently do not change significantly among soil orders. However, the kinds and proportions of exchangeable bases distinguish Solonetzic soils from others. Data for three pedons shown in Tables 17, 18, and 19 indicate relatively high contents of Na^+ and Mg^{2+} in the exchange complex of these soils. Base saturation values are relatively low in the acidic A horizons.

4.6.8 Major Series

A listing of Solonetzic soil series and their mapped areas was obtained from SIDMAP, as explained previously (Section 4.5.8). Series of greater than 100 mapped sections are given in Table 20. The data in this table indicate that the largest areas of Solonetzic soils, particularly Solodized Solonetz, occur in the Brown, Dark Brown, and Black soil zones. Gray and Dark Gray Solodized Solonetz and Solod are common in the Peace River region (yellow land use area). Descriptions of three representative pedons are provided in Tables 17, 18, and 19.

4.6.9 Land Use

The majority of the Solonetzic soils in Alberta are located in areas of mixed farming (Agriculture Canada 1975; Holowaychuk and Fessenden 1986). Wheat, oats, barley, rapeseed, and bromegrass (pasture) are mainly grown on these soils. Crop rotations in the south and south central part of the province are similar to those discussed for the Chernozemic order. Some of the Solonetzic soils in the Brown soil zone are also irrigated and satisfactory yields of potatoes, sugar beets, sweet corn, peas, and cultivated forage crops have been attained. Solonetzic soils in the Peace River region are dominated by barley. Wheat, hay, and canola follow with little acreage differences among them. Crop rotations in this area are four and five year systems involving canola, wheat, and barley followed by a year of summerfallow or a plow down crop (personal communication, Assessment Standards Branch, Alberta Municipal Affairs, 1985). Basically, Solonetzic

Table 15. Reaction (pH) of Solonetzic soils.[1]

Great Group	Layer	$pH(H_2O)$ Range	Most Common pH Range
Solonetz and Solodized Solonetz	Surface	5.1 - 7.3	5.6 - 6.5
(South and South Central Alberta)	Subsoil	5.1 - 7.8+	6.6 - 7.7
Solod - Black and	Surface	5.6 - 6.5	5.6 - 6.5
Dark Gray (Northwest Alberta)	Subsoil	4.6 - 6.0	5.6 - 6.0

[1] Adapted from the original tables in Holowaychuk and Fessenden (1986)

Table 16. Cation exchange properties in the great groups of the Solonetzic order.[1,2]

Great Group	CEC Range (cmol(+)kg^{-1})	Most Common CEC Range (cmol(+)kg^{-1})	Exchangeable Bases Range (cmol(+)kg^{-1})	Most Common Exch. Bases Range (cmol(+)kg^{-1})	Base Sat. (%) Range
Solonetz and Solodized Solonetz (surface)	3-35	12-25	3-30	10-20	50-100
Solonetz (subsoil)	3-35+	15-30	15-35	15-30	80-100
Solod (surface)	20-35	25-35	12-30	20-30	50-90
(subsoil)	25-40	25-40	20-35	20-35	70-100

[1] Adapted from the original tables in Holowaychuk (1986)
[2] Abbreviations: CEC = cation exchange capacity; Exch. = exchangeable, Sat. = saturation

Table 17. Description of a Black Solodized Solonetz - Camrose series.[1,2]
(SW19-49-16-W4; moderately well drained; morainal; fine-loamy to fine-clayey)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
Ah	0-20	very dark brown (10YR 2/2d)	loam	moderate, medium granular	friable	-	clear, smooth
Ae	20-23	dark brown (10YR 3/3m)	loam	strong, medium platy	friable	-	clear, wavy
Bnt	23-50	dark yellowish brown (10YR 3/4m)	clay	strong, coarse columnar	very firm	-	abrupt, smooth
Csak	50+	dark yellowish brown (10YR 3/4m)	clay	-	-	-	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1}) Na	K	Ca	Mg	Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
Ah	5.0	4.8	0.37	5.07	14	1.4	0.2	10.9	2.8	29.2	52	-	33	47	20
Ae	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bnt	6.6	6.4	-	-	-	9.9	0.3	6.6	11.0	26.9	100	-	20	48	32
Csak	7.7	7.7	-	-	-	-	-	-	-	-	-	0.3	29	30	31

[1] Adapted from data gathered during the soil survey of the County of Beaver (Howitt, 1985, pers. comm.)
[2] See Table 9 for explanation of abbreviations and symbols.

Table 18. Description of a Gray Solodized Solonetz - Boyer complex.[1,2]
(Jean d'Or Prairie vicinity; moderately well drained; glaciolacustrine; clayey)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
L-H	5-0	dark grayish brown (10YR 4/2m)	-	-	-	-	abrupt, smooth
Ae	0-13	very pale brown (10YR 7/3m)	silt loam	strong, fine platy	firm	-	abrupt, wavy
AB	13-20	dark reddish brown (5YR 3/3m)	clay	moderate, medium subangular blocky	very firm	-	clear, wavy
Bnt	20-36	dark reddish brown (5YR 3/3m)	clay	moderate, medium columnar and strong, coarse subangular blocky	very firm, hard	-	clear, wavy
BC	36-48	dark brown (7.5YR 4/2m)	clay	strong, fine subangular blocky	very firm	-	clear, wavy
Csk1	48-79	reddish brown (5YR 4/3m)	clay	massive	firm, plastic	-	gradual, wavy
Csk2	79+	dark brown (10YR 3/3m)	clay	stratified	firm, plastic	-	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
L-H	7.0	-	-	-	-	0.0	1.1	46.0	6.7	56.1	96	-	-	-	-
Ae	5.2	-	0.06	0.60	10	0.2	0.1	2.3	2.0	7.8	59	-	23	62	15
AB	4.9	-	0.06	0.90	15	1.9	0.4	6.1	8.2	21.1	79	-	20	36	44
Bnt	6.2	-	0.09	1.32	15	3.2	0.6	10.3	13.8	29.3	95	-	16	30	54
BC	7.4	-	-	-	-	1.9	0.2	13.4	5.7	21.2	100	4.7	19	35	46
Csk1	7.8	-	0.04	-	-	-	-	-	-	-	-	12.2	25	24	51
Csk2	7.8	-	-	-	-	-	-	-	-	-	-	6.9	17	31	52

[1] Adapted from the original table in Scheelar and Macyk (1972)

[2] See Table 9 for explanation of abbreviations and symbols.

Table 19. Description of a Dark Brown Solod - Brownfield series.
(SW17-37-13-W4; moderately well drained; morainal, fine-loamy)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
Ap	0-11	very dark grayish brown (10YR 2.5/2d)	loam	weak, medium cloddy	friable	plentiful	abrupt, smooth
Ahe	11-17	brown (10YR 4/3m)	loam	weak, fine granular	friable	plentiful	clear, smooth
AB	17-25	dark brown (10YR 3.5/3m)	clay loam	weak, fine to medium subangular blocky	friable	few	clear, smooth
Bnt	25-58	dark brown (10YR 3/2.5m)	clay loam	strong, medium prismatic	firm	few	clear, wavy
Ccas	58+	dark grayish brown (10YR 4/2m)	clay loam	massive	firm	-	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
Ap	-	4.7	-	3.10	-	0.3	0.7	8.1	2.8	19.2	62	-	47	33	20
Ahe	-	4.9	-	1.34	-	0.5	0.4	8.6	3.7	16.7	79	-	40	34	26
AB	-	5.3	-	1.03	-	1.0	0.4	8.8	4.5	16.8	88	-	41	31	28
Bnt	-	6.7	-	1.03	-	2.2	0.7	11.1	7.1	20.2	100	-	36	34	30
Ccas	-	7.7	-	-	-	-	-	-	-	-	-	3.1	40	31	29

[1] Adapted from the original table in Wells and Nikiforuk (1986)
[2] See Table 9 for explanation of abbreviations and symbols.

Table 20. Major soil series of the Solonetzic order in the white and yellow land use areas.[1]

Great Group	Subgroup	Textural Family	Series	Mapped Area Sections	km[2]
Solonetz[2]	-	-	-	-	-
Solodized Solonetz	Brown	fine-loamy	Hemaruka	1924	4983
	Dark Brown	fine-loamy	Halkirk	1158	3000
	Black	fine-loamy	Camrose	1104	2859
			Killam	1063	2753
		clayey	Wetaskiwin	208	539
	Dark Gray	fine-loamy	Valleyview	111	287
	Gray	clayey	Lawrence	645	1670
			Boyer	472	1222
	Others[2]	-	-	-	-
Solod	Brown	fine-loamy	Halliday	802	2077
	Black	clayey	Landry	425	1100
	Dark Gray	clayey	Fahler	1095	2836
	Others[2]	-	-	-	-

[1] Adapted from the original tables in SIDMAP (Patterson and Peterson 1984).

[2] Although mapped, total series area is less than 100 sections.

soils have been cultivated much like Chernozemic soils with the exception of deep plowing. This practice mixes portions of the Csk horizon with the A and B horizons. Calcium carbonate is introduced into the Ap horizon and raises the pH to near neutral levels. Microbial activity also increases and root penetration is less restricted. However, because of cost, deep plowing has not become a common practice to date.

4.7 LUVISOLIC ORDER

4.7.1 General Description

Luvisols are soils in which clay illuviation has occurred resulting in light-coloured eluvial A horizons and B horizons in which silicate clays have accumulated. The transfer of clay from the A horizon to the B horizon occurs by physical processes with little or no chemical alteration. The argillic horizon is diagnostic for Luvisolic soils and is identified by: (1) a clay content higher than that of the eluvial horizon as specified by the Canadian system for soil classification and (2) the presence of clay skins (argillans) on one percent or more of the area of a section through the horizon (Expert Committee on Soil Survey 1978). The argillic horizon must also be at least 5 cm thick. Luvisols may have Ah, Ahe, or dark coloured Ap horizons. They also may have a Chernozemic A horizon but it must show evidence of eluviation and be underlain by an Ae horizon which is at least 5 cm thick. Luvisolic soils may not have: (1) a solonetzic B horizon; (2) a podzolic B horizon if the upper boundary of the Bt is at a depth of 50 cm or more from the mineral surface; (3) sufficient gleying to meet criteria of the Gleysolic order; or (4) organic horizons which meet the requirements of the Organic order or permafrost within 1 m of the mineral surface or 2 m in a cryoturbated soil (Expert Committee on Soil Survey 1978).

There are two great groups in the Luvisolic order. Gray Luvisols are predominant in Western Canada. Gray Brown Luvisols, characterized by forest mull Ah horizons developed under deciduous and mixed vegetation occur mainly in the St. Lawrence Lowland. Gray Luvisols usually have L, F, and H horizons, may or may not have an Ah, Ae and Bt horizons, and generally have a mean annual temperature of less than 8°C.

4.7.2 Distribution and Extent

Luvisolic soils in Canada are common in subhumid to humid, mild to very cold climates, on sandy to clayey, base rich parent materials. The largest area of Luvisols occurs in the central to northern Interior Plains. They have formed under deciduous, mixed deciduous-coniferous, boreal forest, or under mixed forest in the forest-grassland transition zone. The Gray Luvisols of this area generally have well developed platy Ae horizons and Bt horizons with moderate to strong blocky mesostructure. Their parent materials are usually calcareous.

Luvisolic soils occupy approximately 203,100 km^2 or about 31% of the province (Holowaychuk and Fessenden 1986). Only about 15% of the cultivated land in Alberta is accounted for by these soils. This proportion could potentially increase up to 40% within the next few decades (Bentley et al. 1971).

The Luvisolic soils of Alberta lie west, north, and northwest of the area of Chernozemic soils. This region is subhumid with adequate precipitation for plant growth but with a limited frost-free period (less than 90 days). Evaporation and transpiration are limited by lower temperatures and by relatively low intensity and incidence of wind. As a result, soils are moist for longer periods of time than in the grassland region. These moister conditions have prevailed and created an environment suitable for trees rather than grasses, and for Luvisolic rather than Chernozemic soils.

4.7.3 Genesis

The dominant process affecting soil formation in Luvisolic soils is lessivage whereby eluviation and illuviation of clay occurs without chemical alteration. Climate and vegetation have a strong influence on this process (Howitt 1981). Under boreal forest vegetation, Ca is thought to be depleted from upper horizons by leaching, and not cycled by plants to as great an extent as in the grassland areas where Chernozemic soils occur (Howitt 1981). This results in moderately acidic conditions. Boreal forest vegetation also contributes less organic matter because litter is mineralized rapidly to organic acids and other compounds of small molecular weight.

The formation of argillic horizons requires that the soil contain fine clays, either produced by weathering or as a component of the parent material. The clays are initially flocculated due to presence of salts or relatively high cation contents. Disruption of the soil and dispersion of clays result from wetting of the soil material. The dispersed clays then move with percolating water and remain where the water stops. Lastly, the clays are plastered on void walls as non-capillary water is drawn from larger voids by capillary withdrawal (Howitt 1981).

The mechanisms involved in lessivage are not clearly understood. Initial mobilization of fine clays has been postulated as being due to deflocculation resulting from depletion of electrolytes, suspension by rapid water movement, and peptization by interaction of organic compounds with clays. Possible mechanisms of clay deposition include drying, gravitational settling, and sieving of clays as suspensions move through fine pores. Factors affecting these processes include wetting-drying cycles, freeze-thaw cycles, soil porosity, type of vegetation, and others. Clay mineral formation, various organo-mineral interactions and redox reactions are other processes which may be involved in formation of Luvisols. These and other factors have recently been reviewed by Buol et al. (1980), Howitt (1981), and Rust (1983). In a study of an Orthic Gray Luvisol near Breton, Alberta, Howitt (1981) found that under present day conditions micaceous clays are being illuviated into the upper Bt horizon. Fine clay sized smectites had migrated into the lower solum during earlier stages of soil genesis. Leaching involved movement of base cations, Fe, Al, and organic constituents, both in solution and in colloidal form.

4.7.4 Mineralogy and Geochemistry

Luvisols, like the Chernozemic and Solonetzic soils discussed previously, have not undergone significant mineral weathering or synthesis. Their mineralogy and geochemistry, therefore, is similar to that of their parent materials. Pawluk (1961) examined the mineralogy of five common soil series developed on glacial till in central and northwestern Alberta and found smectites, illite, and kaolinite to be the predominant clay minerals. Small amounts of mixed layer minerals, chlorite, and quartz were also found in the clay size fraction. The fine sand fraction consisted of quartz, potash-feldspars, and soda-calcic feldspars in the lowest specific gravity component. The intermediate fine sand material was composed of biotite, muscovite, chlorite, and highly weathered amphiboles and pyroxenes. Heavy minerals in the fine sand consisted of iron oxides, amphiboles, garnets, and pyroxenes. The clay mineral composition among Ae, Bt, and C horizons was generally similar; however, the Ae horizons showed depletion of smectites in some profiles. Smectites were dominant in all fine clay (<0.2 μm) fractions. However, illite was present in larger amounts than smectite in the coarse clay (0.2-2 μm) fraction in all horizons of some of the profiles. Howitt (1981) found that Ae horizons of the Breton soil were depleted of smectites and were relatively high in vermiculite and amorphous compounds. The fine clay fraction of the Ae horizons was dominated by mica and amorphous minerals while fine clay-sized smectite was abundant in the Bt horizon. Similar mineral assemblages have been found in other studies of Luvisolic soils in Alberta (e.g., Abder-Ruhman 1980). A thorough review of mineralogical and geochemical studies of soil parent materials in Alberta and adjacent areas can be found in Spiers (1982) and of mineralogy and weathering in Abder-Ruhman (1980).

The elemental content of morainal parent materials of Luvisols was derived, as for Chernozemic and Solonetzic soils previously discussed, from the report of Pawluk and Bayrock (1969). Because they occur over a considerable part of the province, the entire ranges of elemental contents and other properties as reported by these authors can be found for Luvisol parent materials. The ranges of these properties, along with the most common ranges indicated in parentheses, are as follows: CaO, 0 - 20 (2 - 6)%; Fe, 1.5 - 4.25 (2.5 - 3.5)%; Zn, 40 - 110 (60 - 90) mg kg^{-1}; Cu, 5 - 40 (15 - 30) mg kg^{-1}; Mn, 0.015 - 0.045 (0.025 - 0.035)%; Mo, 0 - 3 (1 - 2) mg kg^{-1}; Co, 4 - 9 (6 - 8) mg kg^{-1}; and B, 15 - 60 (30 - 50) mg kg^{-1}. Variable salt content of the tills was indicated by an electrical conductivity range of 0 - 2.5 S m^{-1} although values over most of the province were less than 0.5 S m^{-1}.

The elemental contents of both morainal and glaciolacustrine materials in northeastern Alberta (Spiers 1982) were found to be generally similar to those reported by Pawluk and Bayrock (1969). Data for a number of other elements were also reported by Spiers (1982). Calcium and magnesium contents were found to be lower than those reported for parent materials in other areas; this was attributed to lower carbonate content of sediments in the northeast.

The pH of parent materials as reported by Pawluk and Bayrock (1969) ranges from about 4.0 to 8.5. Parent materials of low pH mainly occur in upland areas such as the Birch Mountains, Buffalo Head Hills and Clear Hills. The glacial till of the Birch Mountains is fine-loamy to clayey and contains much locally derived shaley material (Spiers 1982). Luvisolic soils of low pH and base saturation developed from acidic parent materials which were derived from the weathering of soft gray Cretaceous shales have been described in the Peace River region (Pawluk and Dudas 1978).

In summary, the clay mineral components of the subsoils of Luvisols, as well as of Chernozemic and Solonetzic soils discussed previously, appear to be dominated by smectite minerals, with slightly lesser amounts of micaceous minerals, and minor levels of kaolinite and chlorite. Smectites are commonly depleted in the eluvial layer of Luvisolic soils. Elemental contents are variable but fairly high. Weathering of minerals such as feldspars has been reported in some studies of Luvisolic soils. Clay mineral alteration and synthesis in the upper sola of Luvisols has likewise been reported in some studies. Luvisolic soils with unique properties and processes occur where their development has been influenced by acidic parent materials, by highly carbonitic or saline parent materials, or by the deposition of volcanic ash during their formation.

4.7.5 Biogeochemistry

Biogeochemistry of forested ecosystems is commonly described in terms of pools and fluxes of elements in an ecosystem. Various models have been developed to describe nutrient cycling in ecosystems. These incorporate pools or fluxes or both, either with quantification (budgeted cycles) or without (conceptual flow and compartment models). Ulrich and Mayer (1972) used a systems analytical approach for study of bioelement pools and fluxes which has now become a commonly used method among researchers. Most authors have distinguished between the following main nutrient pools in the analysis of ecosystems: the above-ground tree layer, the ground cover vegetation, the forest floor, and the mineral soil. The above-ground tree layer is commonly subdivided further into foliage, branches, and stem plus bark components. Estimates of nutrients in roots are less common because of difficulties in sampling. Soil bioelements are reported as total amounts and/or labile fractions. A more detailed representation of functional components and nutrient transfers in forest ecosystems is shown in Figure 5. The "canopy solution" compartment in Figure 5 is commonly split into sorbed, throughfall and stemflow components in reports in the literature.

The discussion in this section will apply to forest soils in general. That is, Luvisols will be discussed for the most part but for the sake of enabling comparisons and of avoiding repetition in other sections Brunisols, Podzols, and other forest soil orders are included in this section as well. Moreover, there is now a considerable amount of international literature concerning nutrient cycling in forest systems and a thorough review is not possible in this report. Only some general principles and an indication of sources of information pertinent to Alberta forest soils are discussed herein.

There is little information available about the amounts of nutrient elements in forest soils in Alberta. Luvisols are characterized by a litter (LFH) layer which may be up to 40 cm thick (but is generally less than 20 cm). This layer contains the bulk of the soil organic carbon and total N, P, and S. Brunisolic soils on loamy and clayey materials may have similar litter layers but those developed on sandy parent materials generally have very thin LFH horizons. In these soils, the bulk of organic matter may occur within the mineral solum.

Research in boreal forest ecosystems in other parts of North America has shown that the reserves of nutrients in litter layers are in many instances several times larger than the amounts contained in the standing tree biomass of middle-aged and mature stands. Gordon (1983) found that soil N reserves in a number of forest types in Ontario were substantially higher than in the standing crop. Calcium and magnesium were also generally higher in soils than in standing crops. Conversely, P and K soil reserves were lower than amounts in the standing crop, particularly in organic and sandy soils. It was suggested that those sites with lower nutrient reserves in the soil than in the

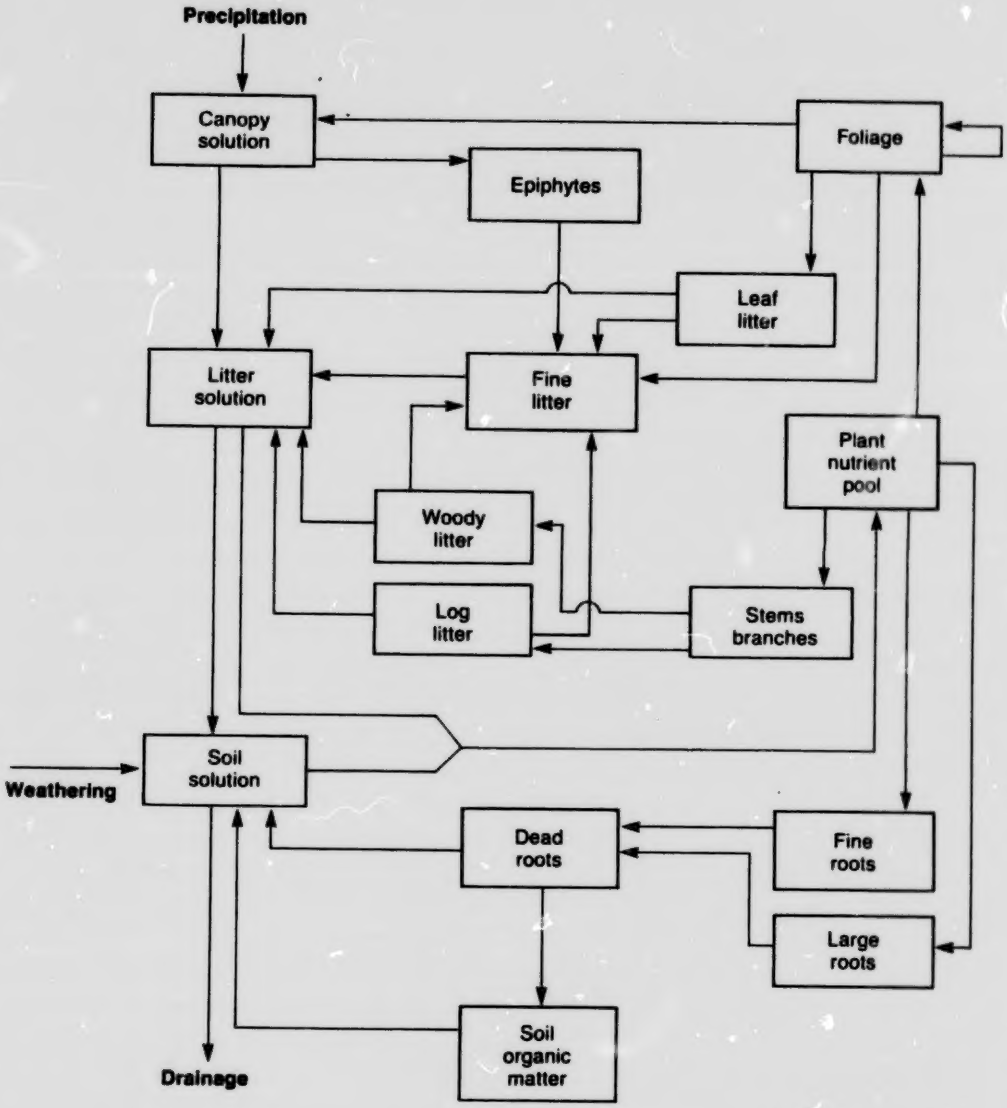
Precipitation
Canopy solution
Foliage
Epiphytes
Leaf litter
Litter solution
Fine litter
Plant nutrient pool
Woody litter
Log litter
Stems branches
Weathering
Soil solution
Dead roots
Fine roots
Large roots
Soil organic matter
Drainage

Figure 5. Diagram of a forest ecosystem showing functional components and nutrient transfers. (Source: Sollins et al. 1980)

standing crop could most likely experience nutrient stress from a disturbance such as tree harvesting. Data for both bioelement pool sizes and cycling rates have been reported by Gordon (1983). Data on black spruce and mixedwood stands on peat, outwash sand, and till may be useful for comparison with Alberta situations. Timmer et al. (1983) provided additional information, mainly in relation to effects of harvesting, on similar stands in the same areas as Gordon's (1983) study sites. Pertinent data on forest stands and soils similar to those occurring in Alberta can also be found in a study conducted in Alaska by Van Cleve et al. (1983).

Climate and types of forest floor litters produced by forest vegetation are major factors affecting rates of nutrient cycling (Krause et al. 1978). Decomposition rates and releases of organically bound nutrients such as N and P are slow because of low mean annual temperatures and substrate composition which is unfavourable to microfauna and microbial attack. The rates of nutrient cycling and associated fertility are thus closely related to the biological controls of organic matter decomposition and accumulation in the forest floor. Moisture conditions affect nutrient cycling such that wet and dry sites have the lowest rates of cycling while moist or fresh sites have relatively rapid rates. Dry, lichen-dominated sites have weak nutrient cycles and may be damaged by excessive nutrient exports. Such sites require conservation of organic matter and associated nutrients. The impact of tree removal, by harvest or by dieback, from wet sites with low nutrient cycling rates may be a rise in water table levels and of paludification.

Further information about biogeochemistry of boreal forest ecosystems can be found in Krause et al. (1978) and Armson (1977). Information about nutrient cycling in Alberta forests must be extrapolated from these and other reports since few studies have been carried out in the province. Cragg et al. (1977) reported a study of cycling in aspen ecosystems in the Canadian Rockies. Nyborg et al. (1985) have reported throughfall and stemflow measurements in jack pine and aspen stands in the Athabasca Oil Sands area. McGill et al. (1980) calculated nutrient fluxes in jack pine and mixedwood sites on sandy Eluviated Eutric Brunisols in the Athabasca Oil Sands area. The uptake and turnover of nutrients was found to be much higher under mixedwood than under jack pine. Nutrient uptake for the mixedwood site was comparable to that of a jack pine stand on a sandy humo-ferro podzol in Ontario reported by Foster and Morrison (1976). Losses due to leaching in these sandy soils were small and K was leached in greater amounts than N, P, Ca, and Mg. Results from the Athabasca Oil Sands area studies show that Brunisolic soils have very low plant nutrient pools and fluxes. Any perturbation to the system which would result in accelerated removal of nutrients from the system could, therefore, have a rapid deleterious effect on forest growth.

4.7.6 Soil Reaction

Luvisolic soils are characterized by moderately acid pH in the LFH, A, and B horizons and by alkaline pH and calcareousness in the C horizon. Exceptions to alkaline reaction within the C horizons occur where these soils have developed in acidic parent materials as described previously. A summary of ranges in pH in surface and subsoil layers of Luvisolic soils is given in Table 21. The ranges are weighted averages for the top 20 cm layer and the layer from 20 cm to the base of the B horizon. Thus, many

Table 21. Reaction (pH) in subgroups within the Gray Luvisol great group in Alberta.[1]

Subgroup	Soil Layer	pH Range	Most Common pH Range
Orthic Gray Luvisol	Surface[2]	<4.6 - 7.3	5.1 - 6.5
	Subsoil	<4.6 - 7.3	5.1 - 6.0
Dark Gray Luvisol	Surface	5.6 - 7.7	6.1 - 6.5
	Subsoil	5.6 - 7.7	5.6 - 6.0
Brunisolic Gray Luvisol	Surface	4.6 - 7.7	5.1 - 6.0
	Subsoil	4.6 - 7.3	5.1 - 6.0
Solonetzic Gray Luvisol	Surface	5.6 - 6.5	5.6 - 6.0
	Subsoil	4.6 - 6.0	5.1 - 5.5

[1] Adapted from the original tables in Holowaychuk and Fessenden (1986)

[2] Surface - weighted averages from 20 cm to base of B.
Subsoil - weighted averages for 20-50 cm depth.

surface layers are averages of LFH, Ae, and A horizons while many subsoils are averages of AB, Bt, and BC horizons. Soil reaction ranges from strongly to slightly acid in both surface and subsurface layers among all the subgroups. Information about the variation in soil reaction among natural soil horizons and among profiles from different areas can be obtained from various soil survey reports and from references cited in this section. Some descriptions of representative Luvisolic soil profiles are provided in Tables 22 to 26 to illustrate distribution of pH and some other properties within profiles.

4.7.7 Ion Exchange Properties

Data for cation exchange capacities and base saturation percentages in Luvisolic soil subgroups are provided for surface and subsoil layers in Table 27. These have been derived from Holowaychuk and Fessenden (1986) in the same way as pH discussed in the previous section. In most cases, subsoils have higher CEC than surface layers. As with pH, portions of Bt horizons may be included in the weighted average for the top 20 cm creating a somewhat higher CEC than in the Ae horizon alone. The distribution of CEC and base saturation is more realistically seen by examination of data for natural horizons as in Tables 22 to 26. Depletion of colloids by eluviation from Ae horizons results in relatively depressed CEC values as compared to lower horizons. The base saturation of both LFH and Ae horizons can also be low. The CEC is usually maximum in the Bt horizon, whereas base saturation is highest in the C horizons.

In a later section in this report, potential impacts of acid deposition on base saturation are calculated on the basis of reactions occurring within the top 25 cm layer of soil. The initial base saturation and the depth of the Ae horizon determine the effects of acid inputs over time. If the Ae is deep and characterized by low CEC and base saturation, the potential impact could be high. If the Ae is shallow, the high CEC and base status of Bt horizons within the top 25 cm will diminish the potential detrimental effect of acid inputs. The Bt horizon material may be incorporated into the plough layer of cultivated Luvisols with thin Ae horizons. Such soils will not be as readily affected by acidic inputs as soils with thick Ae horizons.

4.7.8 Major Series

A list of Luvisolic soil series and their mapped areas is provided in Table 28. Only series of greater than 100 sections of areal extent are listed. The data were obtained from SIDMAP and, therefore, only soils within the white and yellow land use areas are represented. Extensive areas of other Luvisolic soil series outside of this region have been mapped. Information about these can be obtained from soil survey reports. Most of the Luvisolic soils in northern Alberta remain unclassified and unmapped, except at the exploratory level of survey.

4.7.9 Land Use

Luvisolic soils account for about 15% of the cultivated acreage in Alberta (Bentley et al. 1971). Large portions of this land are used to raise livestock, but mixed farming and grain farming are also carried out on these soils. Barley and hay are the dominant crops and occur in rotations of 3-5 years, hay being followed by three years of barley. Other cropping systems are four or five year canola-wheat-barley rotations

Table 22. Description of a Dark Gray Luvisol - Leith series.[1,2] (SW8-54-7-W4; rapidly drained; glaciofluvial; sandy)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
Ahe	0-18	dark to very dark gray (10YR 4/1-3/1d)	loamy sand	weak, fine granular	loose	plentiful	clear, wavy
Ae	18-30	pale brown to brown (10YR 6/3-5/3d)	sandy loam	weak, medium platy	loose	abundant	clear, wavy
Btj	30-51	yellowish brown (10YR 5/4d)	loamy sand	weak, fine subangular blocky to single grain	friable	few	gradual, wavy
BC1	51-86	yellowish brown (2.5Y 5/6m)	sand	single grain	loose		
BC2	86+	yellowish brown (2.5Y 5/6m)	sand	single grain	loose		

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
Ahe	6.5	-	0.26	2.98	11	0.1	0.2	10.5	1.8	13.7	92	-	86	10	4
Ae	6.1	-	0.11	1.15	12	0.0	0.2	5.5	1.2	9.1	76	-	80	9	11
Btj	5.9	-	0.05	0.51	10	0.1	0.2	5.5	1.6	8.8	84	-	86	3	11
BC1	7.4	-	-	-	-	0.1	0.2	3.1	0.7	4.5	91	0.2	92	2	6
BC2	7.2	-	-	-	-	0.0	0.2	2.8	0.6	3.8	95	0.3	94	0	6

[1] Adapted from the original table in Macyk et al. (1985)

[2] See Table 9 for explanation of abbreviations and symbols.

Table 23. Description of an Orthic Gray Luvisol - Culp series.[1,2]
(SW29-56-13-W5; rapidly drained; glaciofluvial and eolian; sandy)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
L-H	5-0	-	-	-	-	-	-
Ae1	0-5	brown (10YR 5/3m)	loamy sand	weak, fine, platy	loose	-	clear, wavy
Ae2	5-23	yellowish brown (10YR 5/4m)	loamy sand	moderate, fine platy	loose	-	abrupt, smooth
Bt	23-38	yellowish brown (10YR 5/8m)	sandy clay loam	weak, medium subangular blocky	friable	-	abrupt, smooth
BC	38-99	grayish brown (2.5Y 5/2m)	loamy sand	single grain	loose	-	abrupt, smooth
Ck	99+	light olive brown (2.5Y 5/4m)	loamy sand to sand	single grain	loose	-	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
L-H	6.4	-	-	-	-	0.2	1.2	26.2	4.1	35.1	90	-	-	-	-
Ae1	6.3	-	0.04	0.58	14	0.0	0.3	4.3	1.0	6.4	87	-	81	12	7
Ae2	6.2	-	0.04	0.29	7	0.0	0.2	4.0	0.7	5.6	87	-	82	12	6
Bt	6.0	-	0.03	0.41	14	0.0	0.4	8.7	2.6	12.9	91	-	71	6	23
BC	6.4	-	-	-	-	0.1	0.2	3.3	1.0	5.3	87	-	85	5	10
Ck	7.1	-	-	-	-	0.0	0.1	4.4	0.3	4.8	-	2.8	88	5	7

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[1] Adapted from the original table in Twardy and Lindsay (1971)
[2] See Table 9 for explanation of abbreviations and symbols.

Table 24. Description of an Orthic Gray Luvisol - Breton series.[1,2]
(SW31-50-7-W5; moderately well drained; morainal; fine-loamy)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
L-H	5-0	very dark grayish brown (10YR 3/2d)	-	-	-	-	-
Ae	0-15	grayish brown (10YR 5/2d)	silt loam	strong, fine to medium platy	soft	-	abrupt, smooth
AB	15-33	pale brown (10YR 6/3d)	clay loam	moderate, fine subangular blocky	slightly hard	-	clear, wavy
Bt1	33-45	yellowish brown (10YR 5/4d)	clay loam	moderate, fine to medium subangular blocky	hard	-	clear, wavy
Bt2	45-112	dark yellowish brown (10YR 4/4m)	clay loam	strong, medium subangular blocky	firm	-	abrupt, wavy
BC	112-150	dark yellowish brown (10YR 4/4m)	loam to clay loam	amorphous	friable	-	abrupt, wavy
Ck	150+	olive brown (2.5Y 4/4m)	clay loam	amorphous	friable	-	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
L-H	-	-	-	-	-	0.0	1.9	96.0	0.0	97.9	100	-	-	-	-
Ae	6.3	-	0.06	0.73	12	0.1	0.6	6.7	0.6	10.5	76	-	26	62	12
AB	5.9	-	0.04	0.31	10	1.7	0.8	13.8	0.6	18.4	92	-	34	37	29
Bt1	5.8	-	0.04	0.46	12	0.0	0.8	16.8	1.9	21.1	92	-	32	35	33
Bt2	5.6	-	0.03	0.28	9	0.1	0.6	16.3	2.6	21.3	92	-	31	36	33
BC	6.0	-	-	-	-	0.2	0.5	16.3	1.6	20.0	93	-	35	38	27
Ck	7.2	-	-	-	-	0.1	0.3	18.0	0.0	18.3	100	3.1	32	40	28

[1] Adapted from the original table in Twardy and Lindsay (1971)
[2] See Table 9 for explanation of abbreviations and symbols.

Table 25. Description of an Orthic Gray Luvisol - Tom Hill series.[1,2]
(NE29-56-16-W5; well to moderately well drained; morainal; fine-loamy)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
L-H	5-0	-	-	-	-	abundant	abrupt, smooth
Ae1	0-5	light brownish gray (10YR 6/2m)	silt loam	strong, fine platy	friable	abundant	clear, wavy
Ae2	5-15	light yellowish brown (10YR 6/4m)	silt loam	moderate, coarse platy to weak, fine subangular blocky	friable	few	clear, wavy
Bt	15-40	yellowish brown (10YR 5/4m)	clay loam	moderate, fine subangular blocky	firm	very few	clear, wavy
BC	40-73	olive brown (2.5Y 4/4m)	loam	weak, fine subangular blocky	firm	-	clear, wavy
C	73+	olive brown (2.5Y 4/4m)	loam	massive	-	-	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
L-H	5.4	5.0	0.90	-	-	0.0	2.9	44.5	1.0	69.4	70	-	-	-	-
Ae1	5.7	5.1	0.04	0.39	10	0.0	0.5	6.9	1.7	10.8	84	-	34	52	14
Ae2	6.1	5.6	0.04	0.38	10	0.0	0.6	13.4	2.9	18.6	91	-	30	52	18
Bt	5.3	5.4	0.04	0.33	8	0.1	0.5	17.8	4.8	25.3	92	-	24	49	27
BC	5.4	5.4	-	-	-	0.1	0.4	17.3	4.3	23.9	92	-	32	43	25
C	5.5	5.5	-	-	-	0.1	0.3	15.3	4.6	21.8	93	-	40	39	21

[1] Adapted from the original table in Dumanski et al. (1972)
[2] See Table 9 for explanation of abbreviations and symbols.

Table 26. Description of a Podzolic Gray Luvisol - Nosehill series.[1], [2]
(SW4-57-17-W5; well to moderately well drained; morainal; fine-loamy)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
L-H	5-0	gray (10YR 6/1m)	-	-	-	abundant	abrupt, wavy
Ae1	0-5	gray (10YR 6/1m)	silt loam	moderate, fine platy	friable	abundant	clear, wavy
Bf	5-10	yellowish brown (10YR 5/8m)	silt loam	weak, fine platy	friable	abundant	clear, irregular
Ae2	10-20	pale brown (10YR 6/3m)	silt loam	strong, fine platy	friable	plentiful	clear, irregular
AB	20-35	light olive brown (2.5Y 5/4m)	silt loam	moderate, coarse platy to subangular blocky	firm	plentiful	clear, wavy
Bt	35-60	yellowish brown (10YR 5/4m)	silty clay loam	moderate, fine subangular blocky	firm	plentiful	clear, wavy
BC	60-100	olive brown (2.5Y 4/4m)	silty clay	moderate, fine subangular blocky	firm	-	gradual, irregular
C	100+	dark yellowish brown (10YR 4/4m)	clay loam	massive	-	-	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
L-H	4.2	3.6	1.26	-	-	0.1	3.7	13.5	1.0	79.3	23	-	-	-	-
Ae1	4.5	3.8	0.06	0.70	12	0.1	0.3	2.3	1.1	11.6	41	-	28	63	9
Bf[2]	5.2	4.4	0.09	1.40	16	0.1	0.4	3.7	1.6	13.9	42	-	30	53	17
Ae2	5.4	4.6	0.05	0.45	9	0.1	0.2	4.7	2.3	10.6	69	-	26	60	14
AB	4.9	4.8	0.04	0.31	8	0.1	0.3	9.4	3.1	15.5	83	-	32	43	25
Bt	5.7	5.0	0.03	0.22	7	0.1	0.4	18.3	6.0	27.6	90	-	14	47	39
BC	4.8	4.6	-	-	-	0.1	0.5	17.1	6.4	28.4	85	-	4	51	45
C	5.5	5.2	-	-	-	0.2	0.4	18.8	4.3	25.8	92	-	24	40	36

[1] Adapted from the original table in Dumanski et al. (1972)

[2] Oxalate Al plus Fe in this horizon is 1.85%.

Table 27. Cation exchange properties in the subgroups of the Gray Luvisolic great group.[1,2]

Soil Subgroup	CEC Range (cmol(+)kg^{-1})	Most Common CEC Range (cmol(+)kg^{-1})	Exchangeable Bases Range (cmol(+)kg^{-1})	Most Common Exch. Bases Range (cmol(+)kg^{-1})	Base Sat. (%) Range
Orthic Gray Luvisol					
(surface)	4-15	10-15	<2-14	6-12	20-100
(subsoil)	6-30	18-27	<4-30	12-28	25-90+
Dark Gray Luvisol					
(surface)	9-33	15-33	8-30	15-30	75-100
(subsoil)	8-33	15-33	8-30	1-30	70-100
Brunisolic Gray Luvisol					
(surface)	<6-20	9-15	<6-15	<6	<25-74
(subsoil)	16-27	18-27	6-25	-	25-100
Solonetzic Gray Luvisol					
(surface)	10-20	10-15	6-25	8-14	60-90
(subsoil)	25-40	25-35	15-30	20-30	50-95

[1] Adapted from the original table in Holowaychuk (1986).

[2] Abbreviations: CEC = cation exchange capacity; Exch. = exchangeable; Sat. = saturation

Table 28. Major soil series of the Gray Luvisolic great group in the white and yellow land use areas.[1]

Soil Subgroup	Textural Family	Series	Mapped Area Sections	km²
Orthic Gray Luvisol	fine-loamy	Braeburn	3497	9059
		Hubalta	2509	6500
		Athabasca	2172	5627
		La Corey	2062	5342
		Davis	1770	4585
		Cooking Lake	1672	4332
		Breton	1069	2769
	coarse-loamy	Codesa (complex)	1068	2767
	fine-clayey	Alcan	726	1881
	clayey	Maywood	527	1365
Dark Gray Luvisol	clayey	Macola	524	1358
	fine-loamy	Spedden	486	1259
	coarse-loamy	Leith	326	845
Brunisolic Gray Luvisol	fine-loamy	Lobley	1024	2653
	sandy	Peppers	146	378
	coarse-silty	Judy	120	310
Podzolic Gray Luvisol	fine-loamy	Wildhay	815	2111
Solonetzic Gray Luvisol	clayey	Donnelly	2618	6782
		Hazelmere	1603	4153
		Cadotte	1492	3865
	fine-loamy	Nakamun	111	287
Gleyed Gray Luvisol	fine-loamy	Bremay	216	559
Undifferentiated	fine-loamy	Errington (association)	153	396
		Torrens (complex)	345	894
	fine-and-coarse-loamy	Copton	411	1065
Other Subgroups[2]	-	-	-	-

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[1] Adapted from the original tables in SIDMAP (Patterson and Peterson 1984).

[2] Although mapped, total series area is less than 100 sections.

followed by a year of plow down (personal communication, Assessment Standards Branch, Alberta Municipal Affairs 1985). Spring wheat is quite common but limited because of the short frost-free period.

The Luvisolic soils lie in range vegetation Zones 4, 5, and 6. Zone 4 is a zone of rough fescue, Zone 5 is parkland, and Zone 6 is brush pastures (Alberta Agriculture 1981). Brush pastures are by far the most common.

At present, Luvisolic soils in Alberta occur mostly in the Green area. The majority of the land with Chernozemic and Solonetzic soils is already cultivated and most expansion of farmland will occur in Luvisolic areas. Within the next few decades, 40% of all cultivated land may be on the Luvisolic soil zone (Bentley et al. 1971). Forestry is the major industry of the Luvisolic soil area. Recreation, hunting, and trapping are other important activities in this area.

4.8 BRUNISOLIC AND PODZOLIC ORDERS

4.8.1 General Description

Soils of the Brunisolic order in the Canadian System of Soil Classification comprise a broad grouping of imperfectly to well drained mineral soils developed under the influence of various kinds of forest, alpine, or tundra vegetation. They occur under climatic conditions ranging from Mesic to Arctic in temperature classifications and from perhumid to semiarid in moisture regimes. The central concept of the order is the development in situ of a prominent brownish Bm horizon with sufficient alteration by hydrolysis, oxidation, or solution to produce significant changes in colour, structure, and composition different from those of an A or C horizon, but with too little evidence of accumulation to meet the illuvial requirements of a textural or podzolic B horizon. However, they include soils with Ae horizons and with weakly expressed horizons of accumulation of either clay (Btj), or amorphous Al and Fe compounds (Bfj), or both. Under virgin conditions Brunisolic soils may have: organic surfaces; LFH horizons; weak or strongly developed, thin or thick, dark-coloured organo-mineral Ah horizons; or light-coloured, thick or thin, Ae or Aej horizons (Clayton et al. 1977; Expert Committee on Soil Survey 1978).

Characterisitics of surface horizons and of parent material form the basis for separation of Brunisolic soils into four great groups: Melanic Brunisols, Eutric Brunisols, Sombric Brunisols, and Dystric Brunisols. Within these four great groups, subdivision into subgroup classification is based on the degree and depth of humus accumulation in the A horizon, the degree of degradation or eluviation of the A horizon, degree of poor drainage (gleization), or cementation in the profile (duric horizon).

Eutric and Melanic Brunisols are developed on high base status, usually calcareous parent materials. They have a pH >5.5 within a depth of 25 cm below the top of the B horizon. Dystric and Sombric Brunisols have pH <5.5 throughout the upper 25 cm of the B horizon, or throughout the B horizon and the underlying material to a depth of 25 cm or to a lithic contact. They are developed from parent materials with little or no lime content. Melanic and Sombric Brunisols are distinguished from Eutric and Dystric Brunisols by the presence of organo-mineral Ah horizons of at least 10 cm thickness. Such horizons develop under forest or grass-forb vegetation where humification and mull formation by mesofauna and microorganisms are important processes.

Podzolic soils are those in which the dominant accumulation product in B horizons is amorphous material composed mainly of humified organic matter combined in varying degrees with hydrous oxides of Al and Fe. Generally, Podzolic soils have LFH, Of, or Om organic surface horizons underlain by a light-coloured, eluvial Ae horizon. A prominent reddish brown to black B horizon is diagnostic for Podzolic soils. The Podzolic B must be at least 10 cm thick and have colour and chemical criteria reflecting accumulation of humus, Al, and Fe as established by the Expert Committee on Soil Survey (1978).

The Podzolic order is divided into three great groups - Humic Podzol, Fero-Humic Podzol, and Humo-Ferric Podzol - based on differing proportions of organic and Fe contents. Subgroups are separated on the basis of kind and sequence of horizons, and on the presence of additional horizons such as orstein, placic, duric, or fragic layers. The eluvial (Ae) horizon may be absent in Podzolic soils.

4.8.2 Distribution and Extent

Brunisolic soils, along with limited areas of Podzols, account for about 52,900 km^2 or about 8% of Alberta's area. Soils of the Montane and Subalpine ecoregions are characterized by moderately well drained, medium textured Eutric Brunisols of varying degrees of development (Strong and Leggat 1981). Brunisols developed on sandy materials of glaciofluvial and eolian origin occur in association with Luvisols in all of the Boreal ecoregions, particularly the Boreal Mixedwood, Boreal Uplands, and Boreal Northlands. Only small areas occur within the Boreal Foothills and Boreal Subarctic ecoregions. A notably large area of Brunisolic soils (mainly Eluviated Dystric Brunisols) occurs south of Lake Athabasca.

Podzolic soils in Alberta are uncommon except in the Subalpine and Alpine ecoregions. They have been mapped mainly in the National Parks ecological inventories. Podzolic soils in these areas are associated with Brunisolic soils under cool, moist Subalpine and Alpine conditions on stable landforms which are commonly morainal with eolian or fluviolacustrine veneers. The Brunisolic-Podzolic complex of soils is most common in the western portion of the mountain parks south of Jasper National Park. Orthic Humo-Ferric Podzols, with Bf horizons, occur at moderate elevations under well to moderately well drained conditions with Engelmann spruce-subalpine fir and subalpine larch forests. The humus contents of podzolic B horizons tend to increase with elevation, and Orthic Ferro-Humic Podzols, with Bhf horizons, are common under heath-tundra vegetation in the Alpine and Alpine-Upper Subalpine zones. Podzolic soils also occur within imperfectly to poorly drained conditions in these areas (Holland and Coen 1983).

Minor occurrences of Podzolic soils may be found in areas of sandy Brunisolic soils in other parts of the province. Brunisolic soils which meet the colour criteria of Podzolic soils, but do not meet the chemical criteria, may also be found. These Brunisolic-Podzolic intergrades occur in imperfectly to well drained conditions under jack pine and related communities typical of Brunisolic soils in the Boreal region.

4.8.3 Genesis

The main processes involved in Brunisolic soil formation are the leaching of soluble salts and carbonates, the weathering of minerals principally resulting in formation of hydrous Al and Fe oxides, and, in finer textured materials, the development of soil structure. The term "braunification" has been used to refer to the release of iron from primary minerals and dispersion of iron oxides in the soil matrix (Buol et al. 1980). This process results in the development of brownish B horizons although the mechanisms involved are not exactly understood. Factors involved in the development of structure of B horizons are: wetting-drying and freeze-thaw cycles which result in development of cracks and fissures and formation of prismatic types of structures; lessivage, by which eluviated A and juvenile textured B horizons are formed; podzolization, by which juvenile Bf horizons form; and hardening, by which voids are filled with cementing materials resulting in formation of duric horizons. Freezing and thawing causes eluviation and platy structure development in the surface mineral horizons of some soils. Soil surfaces most commonly develop mor organic layers or organo-mineral mull horizons.

There are a number of reasons for occurrence of Brunisolic soils within the same regions as Luvisolic soils. At high elevations, cold climates restrict weathering transformations and transport of colloids down profiles. In very sandy parent materials, the colloid content is insufficient for formation of textural horizons and for weathering transformations which produce amorphous Al and Fe oxides. Furthermore, they are relatively droughty and infertile so that vegetative production is low and organic matter additions to soil are insufficient to produce Ah horizons. Brunisolic soils may also occur on recently deposited parent materials in which there has been insufficient time for profiles to develop.

Podzolic soils have formed under subarctic to cryoboreal and perhumid to humid soil climates. Their parent materials are predominantly silica-rich and base-poor coarse eolian and glaciolacustrine sediments. Vegetation on these soils is usually coniferous forest, but at higher elevations or latitudes they develop under heath-tundra vegetation.

Podzolic soils represent the most strongly developed soils in Boreal, Subalpine, and Alpine ecoregions of Alberta. Chemical and biological transformations are intense in the upper horizons and an abundance of water moving through the soil during the year results in considerable leaching. Mineral transformations in podzolization involve the dissolution of ferromagnesian minerals and release of Fe, Al, Mg, Si, and associated elements near the soil surface. Much of the liberated Al and Fe is complexed with organic matter, translocated downward and deposited in the B horizon. The Mg and Si leach out of the soil with the drainage water. Continued mineral weathering and translocation of the products apparently occurs through the action of simple organic acids and of fulvic and humic acids in the soil. Processes include mineral attack, formation of organo-mineral complexes, precipitation of complexes and attack of B horizon material by uncomplexed organic matter. These processes have been reviewed by Buol et al. (1980) and McKeague et al. (1983). More recent research has indicated that transitional mineral weathering products such as imogolite are produced during Podzol formation (Farmer et al. 1985).

4.8.4 Chemical and Physical Properties

Little information is available about the mineralogical and geochemical properties of Brunisols and Podzols in Foothills, Subalpine, and Alpine regions. Elsewhere, these soils have developed on predominantly sandy materials whose main constituents are quartz and lesser amounts of feldspars. A review of research on mineralogy and weathering in Brunisolic soils is included in the thesis of Abder-Ruhman (1980).

Descriptions of profiles from typical Brunisolic and Podzolic soils are provided in Tables 29 to 32 to demonstrate some of their properties. Soil reaction, or pH, is generally low in Ae and Bm horizons. It increases to alkaline pH levels in the Eutric Brunisol great groups but remains below neutrality to greater depths in Dystric Brunisols. Summaries of soil reaction in Brunisolic and Podzolic soils as derived from Holowaychuk and Fessenden (1986) are presented in Table 33. The pH of Podzolic soils appears to be generally lower than that of Brunisols.

Notable aspects of ion exchange properties from the example profile tables (29 to 31) and from the summary in Table 34 are: very low CEC and total bases in sandy Brunisolic soils; low base saturation in surface horizons; an increase of base saturation with depth, particularly in Eutric Brunisols; and extremely low levels of exchangeable bases and of base saturation in Podzolic soils.

The description of a Podzolic soil profile in Table 32 shows the relatively high levels of organic carbon and of pyrophosphate soluble Fe and Al in the B horizon. As indicated previously in Section 3.3, amorphous hydrous oxides of Fe and Al have a high capacity for sorbing phosphates, sulphates, and other anions. The levels of these materials in Podzolic soils, as well as in Brunisolic soils with podzol-like B horizons, need to be considered in evaluations of potential effects of acid deposition on them.

4.8.5 Major Series and Land Use

Only series within the Eutric and Dystric Brunisol great groups have been mapped over significant areas in Alberta. Those occurring within the area covered by SIDMAP are indicated in Table 35. The Heart complex refers to complexes of Brunisolic and associated Regosolic and Podzolic soils developed in eolian parent materials. This mapping unit has been applied to soil inventories throughout the Boreal forest region. Soil units other than those indicated in Table 35 include Mildred (Brunisols on sandy glaciofluvial materials) and Firebag (Brunisols on sandy and stony, glaciofluvial ice contact deposits). Both of these have been mapped in the Athabasca oil sands area (Turchenek and Lindsay 1982). Podzolic soils which have been mapped in Western Alberta include the Hornbeck and Baptiste series (Dumanski et al. 1972).

Most Brunisolic soils are under native forest or heath vegetation. The productivity of sandy Brunisols in the Boreal regions is low and little forest production is derived from them. Fine-textured Brunisolic soils of the Foothills and Subalpine regions support timber such as lodgepole pine and fir, which are used for timber, pulp, and paper. Most Brunisolic and Podzolic soils are thus in their natural state. As such, these soils and the forests and landscapes they are associated with are valued for wildlife habitat and for recreational purposes.

4.9 ORGANIC AND ORGANIC CRYOSOLIC SOILS

4.9.1 General Description

Soils of the Organic order are those which contain more than 30% organic matter (17% organic carbon) and extend to a depth of at least 60 cm if the surface layer

Table 29. Description of an Eluviated Eutric Brunisol - Blackmud series.[1,2] (SW25-68-5-W6; rapidly drained; glaciofluvial; sandy)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
L-H	5-0	-	-	-	-	abundant	gradual, wavy
Ae	0-7	light brown (7.5YR 6/4m)	sandy loam	single grain	very friable	abundant	clear, wavy
Bm1	7-25	strong brown (7.5YR 5/6m)	sandy loam	very weak, fine subangular blocky	very friable	plentiful	gradual, wavy
Bm2	25-49	yellowish brown (10YR 5/6m)	loamy sand	single grain	very friable	plentiful	diffuse, broken
BC	49-112	brown to dark brown (10YR 4/3m)	loamy sand	single grain	very friable	few	abrupt, smooth
Ck	112+	grayish brown (10YR 5/2m)	sand	single grain	very friable	very few	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
L-H	5.8	-	0.68	17.11	25	0.1	1.8	29.7	3.3	52.8	66	-	-	-	-
Ae	6.2	-	0.02	0.40	20	0.0	0.1	2.3	0.4	4.5	62	-	70	28	2
Bm1	5.6	-	0.02	0.31	16	0.0	0.2	1.6	0.4	6.3	35	-	73	19	8
Bm2	6.0	-	0.02	0.14	7	0.0	0.2	2.7	1.0	5.8	67	-	84	9	7
BC	6.2	-	-	-	-	0.0	0.2	3.9	0.6	5.8	81	-	84	10	6
Ck	7.8	-	-	-	-	-	-	-	-	-	-	9.6	87	9	4

[1] Adapted from the original table in Twardy and Corns (1980)
[2] See Table 9 for explanation of abbreviations and symbols.

Table 30. Description of an Eluviated Dystric Brunisol - Firebag series.[1,2]
(SW20-104-5-W4; rapidly drained; glaciofluvial; sandy)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
LFH	1-0	-	-	-	-	-	clear, smooth
Ae	0-6	gray (10YR 5/1d)	sand	single grain	loose	plentiful	clear, broken
AB	6-16	very pale brown (10YR 6/3d)	sand	single grain	loose	few	clear, wavy
Bm1	16-30	yellow (10YR 6/6d)	sand	single grain	loose	few	gradual, wavy
Bm2	30-50	very pale brown (10YR 6/4d)	sand	single grain	loose	very few	gradual, smooth
BC	50-100	pink (5YR 8/3d)	sand	single grain	loose	very few	diffuse, smooth
C	100-160+	pink (5YR 8/3d)	sand	single grain	loose	very few	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
LFH	4.3	3.7	0.39	36.97	95	0.5	2.0	8.1	2.8	46.7	29	-	-	-	-
Ae	4.9	3.9	0.02	0.49	24	0.3	0.0	0.3	0.1	2.3	31	-	99	1	0
AB	5.0	4.3	0.01	-	-	0.0	0.0	0.0	0.1	0.4	35	-	97	3	0
Bm1	5.5	4.8	0.00	-	-	0.0	0.0	0.0	0.1	0.5	22	-	98	2	0
Bm2	5.6	5.0	-	-	-	0.0	0.0	0.0	0.0	0.3	-	-	99	1	0
BC	5.8	4.9	-	-	-	0.0	0.0	0.0	0.0	0.2	-	-	100	0.5	0
C	5.8	4.8	-	-	-	0.0	0.0	0.1	0.0	0.1	-	-	100	0.5	0

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[1] Adapted from the original table in Turchenek and Lindsay (1983)
[2] See Table 9 for explanation of abbreviations and symbols.

Table 31. Description of an Eluviated Dystric Brunisol - Robb series.[1,2]
(NE19-59-8-W6; well drained; morainal - Cordilleran; fine-loamy)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
L-F	3-0	-	-	-	-	abundant	abrupt, wavy
Ae	0-10	brown (10YR 5/3m)	loam to clay loam	single grain	very friable	few	clear, wavy
Bfj	10-22	yellowish brown (10YR 5/6m)	clay loam	weak, fine subangular blocky to single grain	friable	plentiful	clear, wavy
Btj	22-40	light yellowish brown (2.5Y 6/4m)	loam	weak to moderate, fine subangular blocky	friable	plentiful	gradual, wavy
BC	40-66	light yellowish brown (2.5Y 6/4m)	loam	weak, fine subangular blocky	friable	few	diffuse, wavy
C	66+	dark grayish brown (10YR 4/2m)	loam	weak, fine angular blocky	friable	very few	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
L-F	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ae	4.3	-	0.10	1.83	18	0.0	0.3	1.5	0.6	18.8	13	-	38	35	27
Bfj	4.9	-	0.06	0.93	14	0.0	0.2	1.3	0.6	19.6	11	-	40	30	30
Btj	4.9	-	0.03	0.33	11	0.0	0.2	4.2	1.4	17.8	33	-	43	31	26
BC	4.8	-	0.03	0.32	11	0.0	0.2	6.2	1.7	18.1	45	-	42	32	26
C	5.0	-	-	-	-	0.1	0.2	12.1	2.3	19.6	75	-	44	30	26

[1] Adapted from the original table in Twardy and Corns (1980)
[2] See Table 9 for explanation of abbreviations and symbols.

Table 32. Description of an Orthic Humo - Ferric Podzol.[1,2]
(Lake Louise vicinity; moderately well drained; coarse-loamy eolian overlying skeletal and coarse-loamy morainal materials)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
Ah	0-4	-	silt loam	weak, fine granular	very friable	abundant	abrupt, wavy
Ae	4-7	pale brown (10YR 6/3m)	silt loam	weak, medium platy	very friable	plentiful	abrupt, wavy
Bf	7-19	yellowish red (5YR 4/6m)	silt loam	moderate, very fine granular	very friable	plentiful	clear, wavy
IIBm	19-40	strong brown (7.5YR 5/6m)	loam	moderate, medium subangular blocky	friable	few	gradual, wavy
IIBC	40-58	yellowish brown (10YR 5/4m)	loam	weak, medium subangular blocky	friable	very few	gradual, wavy
IIC	58-99	brown (10YR 5/3.5m)	loam	massive	friable	very few	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
Ah	-	4.4	-	15.90	-	0.2	0.8	4.5	1.5	42.1	17	-	18	64	18
Ae	-	4.3	-	2.50	-	0.1	0.1	0.4	0.3	11.3	8	-	31	56	12
Bf	-	4.8	-	3.40	-	0.1	0.1	0.5	0.2	21.7	4	-	28	60	12
IIBm	-	4.4	-	0.70	-	0.1	0.1	0.3	0.1	5.2	12	-	42	39	19
IIBc	-	4.3	-	-	-	0.1	0.1	0.4	0.2	4.4	18	-	43	40	17
IIC	-	5.5	-	-	-	0.1	0.1	2.4	1.5	4.2	98	-	42	41	17

	Pyrophosphate Extractable	
	Fe (%)	Al (%)
Bf	0.5	0.3
IIBm	0.3	0.1

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[1] Adapted from the original table in Walker et al. (1982)
[2] See Table 9 for explanation of abbreviations and symbols.

Table 33. Reaction (pH) in soils of the Brunisolic and Podzolic orders in Alberta.[1]

Soil	Soil Layer	pH Range	Most Common pH Range
Dystric Brunisol	Surface	<4.6-6.0	4.6-6.0
Great Group	Subsoil	4.6-6.0	5.1-6.0
Eutric Brunisol	Surface	5.6-7.8+	6.1-6.5
Great Group	Subsoil	6.1-7.8+	6.1-7.3
Podzolic Order	Surface	4.6-5.0	-
	Subsurface	4.6-5.0	-

[1] Adapted from the original tables in Holowaychuk and Fessenden (1986).

Table 34. Cation exchange properties in Brunisolic and Podzolic soils.[1,2]

Great Group	CEC Range (cmol(+)kg^{-1})	Most Common CEC Range (cmol(+)kg^{-1})	Exchangeable Bases Range (cmol(+)kg^{-1})	Most Common Exch. Bases Range (cmol(+)kg^{-1})	Base Sat. (%) Range
Dystric Brunisol					
(surface)	<4-25	<4-6	1-6	<6	<25-60
(subsoil)	<4-25	<6	<2-12	<2	30-50
Eutric Brunisol					
(surface)	<5-25	<5-25	<4-25	<4-25	60-100
(subsoil)	<3-27	15-20	<3-25	15-20	75-100
Podzolic					
(surface)	<6	-	<1	-	<20
(subsoil)	6-10	-	<1	-	<10

[1] Adapted from the original tables in Holowaychuk (1986).
[2] Abbreviations: CEC = cation exchange capacity; Exch. = exchangeable; Sat. = saturation

Table 35. Major soil series of the Brunisolic order in the white and yellow land use areas.[1]

Soil Subgroup	Textural Family	Series	Mapped Area Sections	km²
Eluviated Eutric Brunisol	sandy	Nicot	237	614
	coarse-loamy	Bickerdike	169	438
Eluviated Dystric and Eutric Brunisols	sandy	Heart	1098	2844
Other subgroups[2]	–	–	–	–

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[1] Adapted from the original tables in SIDMAP (Patterson and Peterson 1984).

[2] Although mapped, total series area is less than 100 sections.

consists of fibric material, to a depth of at least 40 cm if the material is mesic or humic, or to 10 cm or more if the organic material overlies rock (Expert Committee on Soil Survey 1978). The material of Organic soils is usually called peat, and is defined as unconsolidated material consisting largely of undecomposed or only slightly decomposed organic matter accumulated under conditions of excessive moisture. Organic soils may also contain muck, a broad term referring to highly decomposed peat with a high proportion of mineral material.

The organic order is subdivided into great groups and subgroups on the basis of degree of decomposition of the organic materials and on the sequence and proportions of horizons within specific layers to a depth of 160 cm. Classes of materials based on degree of decomposition are fibric, mesic, and humic (see Glossary, Section 9). The Organic great groups separated according to degree of decomposition are Fibrisols, Mesisols, and Humisols. A fourth great group, Folisols, is distinguished by nonsaturation and by its composition of forest debris overlying mineral soil on rock. This latter great group is not found in Alberta.

Soils of the Cryosolic order are formed in either mineral or organic materials, and have permafrost either within 1 m of the surface or within 2 m if they are cryoturbated. They have a mean annual temperature below 0°C. The Cryosolic order is divided into three great groups based on the degree of cryoturbation and on the nature of the material. Turbic Cryosols are developed in mineral materials and show marked cryoturbation. Static Cryosols also develop in mineral materials but show no significant cryoturbation. Organic Cryosols are developed in peat and have permafrost within 1 m of the surface. Turbic and Static Cryosols occur principally in the Arctic and at high mountain elevations. Only the Organic Cryosol great group occurs in the plains region in northern Alberta. Cryosolic great groups are further divided into subgroups on the basis of kind and degree of other pedogenetic processes in the profile and on the degree of decomposition of organic materials (Expert Committee on Soil Survey 1978).

4.9.2 Distribution and Extent

Landscapes in which Organic soils account for more than half of the land area occupy about 104,600 km^2, or 16%, of Alberta's area. A further 43,900 km^2, or 6-7%, are occupied by Organic Cryosol dominated landscapes. The sum of these figures, derived from the map of Holowaychuk and Fessenden (1986), is slightly higher than the peatland area estimate of 126,700 km^2, or 19%, indicated by Tarnocai (1983). These figures are rather crude estimates because most of the Organic soils in Alberta occur in the north for which only exploratory survey information is available.

Organic soils occur throughout the forested regions of the province. They occur most commonly in depressions in the landscape, but may also fully occupy extensive lowland areas in northern Alberta. Extensive areas of Organic soils occur in the Boreal Mixedwood, Boreal Uplands, and Boreal Foothills ecoregions (Strong and Leggat 1981). Permafrost may occur in some unique situations but is more common in the Boreal Northlands ecoregion. Organic Cryosols occupy about 50% of the landscape in the Boreal Subarctic ecoregion. Further information on the distribution of peatlands can be found in Wetland Working Group (1981) and Zoltai and Pollett (1983), and on the distribution of permafrost in peatlands in Lindsay and Odynsky (1965).

Mineral Cryosolic soils occur in the Subalpine ecoregion in medium-textured morainal materials on steep, northerly-facing, forested slopes of the Rocky Mountains. Various subgroups of Static Cryosols are represented. These often have surface organic (LFH) layers and are generally imperfectly drained (Holland and Coen 1983).

4.9.3 Genesis

Organic soils, or peatlands, are systems in which the rate of production of organic materials by living organisms exceeds the rate at which they are respired and degraded. The result is an accumulation of a proportion of this production as an organic or peat deposit. As peat thickens, the surface vegetation becomes isolated from underlying soils and rocks, and the resulting environmental changes are often accompanied by floristic changes which reflect the altered hydrology and chemistry of the peat surface (Moore and Bellamy 1974). Most organic soils have developed under highly water-saturated conditions. Where the soil is saturated for only part of the year Organic soils grade into mineral Gleysolic soils with only a thin surface accumulation of peat.

There have been two basic mechanisms of peatland development proposed - terrestrialization and paludification. Terrestrialization is the formation of a peatland system by filling of a water body with organic remains, usually by gradual extension of peat-forming communities inwards from the shoreline of a lake. Paludification literally means "swamping" and refers to formation of peatland systems over previously forested land, grassland or even base rock, due to climatic or authigenic processes (Gore 1983). It is probable that both these processes have contributed to development of peatlands in Alberta. Under saturated conditions, organic materials decompose at slow rates due to lack of oxygen and cold temperatures. Peat has insulating qualities which can keep subsoil layers frozen during the summer. In colder climates, where the temperature of the soil remains below 0°C continuously for a number of years, the lower part of the profile will remain continuously frozen. Where these conditions occur, plateau landforms develop through elevation of the peat mass by volume increase due to freezing and by buoyancy of the frozen peat. The elevation increases the insulation value of peat due to drying of the surface layers (Zoltai 1972). The conditions of low temperatures, high insulating value of peat, and low precipitation thus lead to formation of Organic Cryosols.

Different types of Organic soil material, or peat, are recognized according to the types of vegetation they have developed from. Four main types of peat are commonly recognized in Canada. Sphagnum (or bog) peat consists of the remains of various Sphagnum moss species. Fen peats are generally a combination of sedge- and brown moss-derived materials. Forest peat is derived from debris of tree and shrub species, often intermixed with forest floor materials such as feather-mosses and lichens. Sedimentary (or aquatic) peat is formed by deposition of fine organic materials in water bodies; it is sometimes found as a basil deposit in peatlands. Sphagnum peats are generally poorly decomposed and soils in these materials are, therefore, mainly classified as Fibrisols. Fen and forest peats in Alberta may be slightly or moderately decomposed and soils in these belong to both Fibrisol and Mesisol great groups. Humic materials occur somewhat less extensively than fibric or mesic peats and are most commonly found at the base of peat deposits or in shallow peats.

4.9.4 Chemical and Physical Characteristics

Excellent reviews of the chemical and physical attributes of Organic soils can be found in Walmsley (1977) and Clymo (1983), and in books such as that of Fuchsman (1980) and the Soil Science Society of America special publication edited by Stelly (1974).

Summaries of soil reaction and of cation exchange properties of Organic soils, as derived from Holowaychuk and Fessenden (1986) are presented in Table 36. Descriptions of a representative profile of a Fibrisol in sphagnum peat and of a Mesisol in fen peat are given in Tables 37 and 38. An Organic Cryosol is described in Table 39.

The chemical composition of a peat is largely determined by the botanical composition, the state of humification, and the mineral content of the water associated with the formation of the deposit. The pH of peat ranges from about 3.0 to 8.0, with bog (sphagnum) peats in the lower part of the range (up to about 4.5) and fen peats generally about 4.5 to 7.0. Higher pH values are rare but occur in unique situations. The cation absorption capacity of peats on a weight basis is generally higher than that of mineral soils. When expressed on a volume basis, however, the cation absorption capacity is generally low and is similar to that of sandy soils. The exchange capacity and total exchangeable bases are thus relatively low if expressed on a volume or areal basis.

The pH range in Alberta peats is about 3.0 to 7.5 (Table 36). The low pH ranges typify Organic soils of bogs and Organic Cryosols of permafrost terrain. Higher pH ranges are characteristic of fen and forest peats. Cation exchange capacities are high in all peats (Table 36). However, much of the CEC is pH-dependent and the degree of base saturation is lowest for sphagnum (bog) peats and highest for fen peats. The impact of acid deposition on Organic soils is a concern because of possible base loss from systems that are already low in base status. In considering these impacts, however, the replenishing ability of water associated with Organic soils must be taken into account. This has been done in assessments of soil sensitivity to acidification by Holowaychuk and Fessenden (1986).

Comparing other properties of peats, those composed predominantly of sphagnum have lower ash content, higher carbon, lower nitrogen, and higher C:N ratios than fen or forest peats. Total elemental contents are generally higher in fen and wood peats than in bog peats. With an increase in the degree of decomposition, the carbon content of peat decreases while that of most other elements increases. Thus, the ash content increases and the C:N ratio decreases with higher levels of humification. With increasing humification, the pH and cation exchange capacities of peat also increase.

Physical properties of peat are also dependent on degree of decomposition and botanical composition. Fiber content is the criterion by which peats are subdivided into slightly, moderately, and well decomposed types. Moisture retention of fibric sphagnum peats is generally higher than that of fen peats or of other more decomposed peats. The typical characteristics of a peat high in fiber are high void ratio and air capacity and low bulk density and ash content. With decomposition, bulk density and ash content increase while void ratio decreases. The hydraulic conductivity of fibric peat is quite high while that of well humified peats is low. Hydraulic conductivities ranging from 0.07 cm h^{-1} to 20.3 cm h^{-1} have been recorded for peats in Alberta (Kong et al. 1980).

Table 36. Soil reaction (pH) and cation exchange properties of Organic and Organic Cryosolic soils.[1,2]

		Cation Exchange Capacity		Base	Pool Water	
Layer (cm)	pH(H_2O)	cmol(+)kg^{-1}	cmol(+)L^{-1}	Sat.(%)[2]	pH	Ca + Mg (cmol(+)L^{-1})
		Organic Soils - Eutrophic (Fens and Swamps)				
0-40	6.1-7.8	120-160	9-12	70-100	6.6-7.8	2-5
40-120	6.1-7.3	120-175	10-18	65-100		
120+	6.1-7.3	120-175	10-18	65-100		
		Organic Soils - Mesotrophic (Fens)				
0-40	4.6-6.0	120-160	9-12	25-70	5.1-6.5	0.5-2.5
40-120	5.1-6.5	120-175	15-20	30-70		
120+	5.6-6.5	120-175	15-20	40-75		
		Organic Soils - Oligotrophic (Bogs)				
0-40	<4.5-5.5	120-160	9-12	10-25	<4.5-6.0	<0.5
40-120	<4.5-5.5	120-175	15-20	15-40		
120+	4.6-6.0	120-175	15-20	25-70		
		Organic Cryosols - Oligotrophic (Bogs)				
0-40	<4.5-5.5	125-200	9-15	5-50	<4.5-5.5	<0.5
40-80	<4.5-5.5	140-200	10-15	5-60		
80+	4.6-6.0	140-200	10-15	15-90		

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[1] Adapted from the original table in Holowaychuk (1986).
[2] Sat. = saturation

Table 37. Description of a Typic Fibrisol - Kenzie complex.[1,2]
(SE13-66-25-W4; poorly drained; organic - bog peat)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
Of1	0-15	pink (7.5YR 8/4m)	-	medium fibered	nonsticky	plentiful	abrupt, smooth
Of2	15-40	brown (7.5YR 5/4m)	-	medium fibered	nonsticky	very few	clear, smooth
Of3	40-110	reddish yellow (7.5YR 6/6m)	-	medium matted	nonsticky	very few	clear, smooth
Of4	110-155	dark brown (7.5YR 3/4m)	-	medium fibered	nonsticky	none	clear, smooth
Om	155-170	very dark grayish brown (10YR 3/2m)	-	medium matted	nonsticky	none	clear, smooth
IICg	170-180+	gray (2.5Y 5/1m)	sandy clay loam	massive	very sticky	none	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC[3] (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
Of1	-	3.1	0.56	54.5	97	0.1	1.8	8.4	5.2	163.3	9	-	-	-	-
Of2	-	3.4	0.99	52.2	53	0.1	1.0	22.2	6.7	145.2	21	-	-	-	-
Of3	-	4.2	1.49	56.4	38	0.1	0.1	54.2	12.2	172.2	39	-	-	-	-
Of4	-	4.8	2.38	56.6	24	0.1	0.1	59.4	10.2	162.8	43	-	-	-	-
Om	-	5.2	-	52.3	-	0.1	0.1	64.2	8.0	173.0	42	-	-	-	-
IICg	-	6.4	-	0.8	-	-	-	-	-	-	-	-	-	-	-

[1] Adapted from the original table in Turchenek et al. (1984)
[2] See Table 9 for explanation of abbreviations and symbols.
[3] Determined by the BaCl2 - triethanolamine (pH 8.0) method

Table 38. Description of a Terric Humic Mesisol - St. Lina complex.[1,2]
(SW27-63-10-W4; very poorly drained; organic - fen peat)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
Of	0-25	-	-	medium fibered	-	-	-
Om1	25-51	dark reddish brown (5YR 3/4m)	-	medium fibered	slightly sticky, plastic	-	-
Om2	51-97	dark brown (7.5YR 4/2m)	-	medium fibered	slightly sticky, plastic		
Oh	97-137	dark reddish brown (5YR 3/2m)	-	fine fibered	sticky, plastic	-	-
IICg	137+	-	clay loam	-	-	-	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1}) Na	K	Ca	Mg	Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
Of	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Om1	6.3	-	2.27	40.02	18	0.2	0.8	70.3	28.2	132.3	75	-	-	-	-
Om2	5.8	-	2.86	45.43	16	0.1	0.2	45.3	15.2	103.5	59	-	-	-	-
Oh	5.7	-	1.82	42.69	23	0.2	0.2	34.4	12.3	75.5	62	-	-	-	-
IICg	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

[1] Adapted from the original table in Kocoaglu (1975)
[2] See Table 9 for explanation of abbreviations and symbols.

Table 39. Description of a Fibric Organic Cryosol - Mikkwa complex.[1,2]
(NE5-102-15-W4; poorly drained; organic - forest and bog peat)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
Of	0-42	very pale brown (10YR 7/3m)	-	-	-	-	-
Ofz1	42-116	pale brown (10YR 6/3m)	-	massive; ice lenses	hard	-	-
Ofz2	116-160	brown (10YR 5/3m)	-	massive	hard	-	-
Omz1	160-242	very dark brown (10YR 2/2m)	-	massive; ice lenses	hard	-	-
Omz2	242-300	very dark brown (10YR 2/2m)	-	massive; ice lenses	hard	-	-
Omz3	300-316	black (10YR 2/1m)	-	fine, amorphous	hard	-	-
IICgz	316+	gray (10YR 5/1m)	sandy loam	massive	-	-	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
Of	-	3.8	0.50	50.2	100	0.3	1.6	9.0	1.1	140.4	5	-	-	-	-
Ofz1	-	4.0	0.79	54.1	69	0.3	0.4	37.6	1.1	91.0	26	-	-	-	-
Ofz2	-	5.0	0.99	55.7	56	0.4	0.4	63.1	5.5	90.4	46	-	-	-	-
Omz1	-	5.5	1.00	50.1	50	1.7	0.2	95.1	10.4	142.9	45	-	-	-	-
Omz2	-	5.5	1.01	53.0	53	1.2	0.2	116.8	10.7	147.6	52	-	-	-	-
Omz3	-	5.8	1.34	38.5	29	0.6	0.1	88.2	7.8	112.6	52	-	-	-	-
IICgz	-	5.6	-	-	-	-	-	-	-	-	-	-	-	-	-

[1] Adapted from the original table in Turchenek and Lindsay (1983)
[2] See Table 9 for explanation of abbreviations and symbols.

4.9.5 Major Series and Land Use

For mapping purposes, Organic soils have been mainly designated as "Organic", or as being derived from sphagnum mosses (Kenzie soil complex) or from sedges (Eaglesham soil complex). In soil surveys carried out prior to about 1950, sedge and moss peats were not separated on maps because they were so intermingled. Thus, only one map unit, "Organic", was used to show the location and extent of these soils. Throughout the 1950's, 1960's and 1970's, in mapping projects of the Peace River area and parts of west central Alberta, the Kenzie and Eaglesham soil complexes were used to distinguish the two major Organic soil types. The soil survey of the Hinton-Edson sheet (NTS sheet 83F) was an exception in that a new soil complex name (Fickle) was used to map all Organic soils in the area (Dumanski et al. 1972). This was done to distinguish the somewhat different Organic soils of the upland Alberta Plateau and Rocky Mountain Foothill areas from Kenzie and Eaglesham soils which occur in the lower lying plains of the rest of northern Alberta. In the Tawatinaw (NTS sheet 83I) survey, Organic soils were differentiated into Fibrisols and Mesisols (Kjearsgaard 1972). Organic soil map units were not described according to type of parent material because a variety of materials could generally be found at any one site in the region. Relatively detailed mapping of Organic soils was carried out in the soil survey of the Sand River Sheet (NTS sheet 73L) in which 10 mapping units were described (Kocaoglu 1975).

The soils of most of northern Alberta (the nonagricultural area or Green Zone) were surveyed at an exploratory level during the 1950's and 1960's by Lindsay and others (1958 - 1964). Maps at a scale of about 1:750,000 show major landforms and surficial materials, including organic deposits. The soil types and estimates of percentage of Organic soils are presented in the descriptive parts of these reports.

During the northern exploratory soil surveys, the presence of frozen layers was recognized as an important property of Organic soils and a study of the distribution and some characteristics of frozen soils was subsequently carried out. In the uplands of the most northerly parts of the province the Organic soils were permanently frozen. The depth of the active layer or the depth of annual thaw in these soils was found to be about 50 to 60 cm. In the lower lying and more southerly regions, the organic soils in about 60% of the sites examined were permanently frozen with the depth of the active layer averaging 60 cm. Further south, a third area was recognized in which Organic soils thawed at a relatively rapid rate and the frozen layer usually disappeared by mid or late July (Lindsay and Odynsky 1965).

Within the agricultural areas of the province, about 1566 sections (4056 km^2) of Eaglesham soils and about 3644 sections (9438 km^2) of the Kenzie complex have been mapped (data from SIDMAP, Patterson and Peterson 1984). Some areas have been cleared and drained, and are used for pasture and forage production. Areas and land use of Organic soils by different counties have been reviewed by Turchenek and Marciak (1985). Experimentation is being carried out in drainage and water level control in peatlands as a means of improving commercial timber production. Most of the area of peatlands in the province as a whole, however, is in a natural state and is disturbed only where roads, seismic lines, pipelines and similar developments run through them.

4.10 GLEYSOLIC ORDER

Soils within the Gleysolic order are poorly drained mineral soils whose profiles reflect the influence of waterlogging over significant periods of time. They develop under various climatic and vegetative conditions in the presence of a high or fluctuating water table which produces reducing conditions due to lack of aeration. Gleysolic soils are characterized throughout the profile by dull grayish colours frequently accompanied by prominent, usually rusty coloured mottles resulting from localized oxidation and reduction of hydrated iron oxides. Gleysolic soils develop in poorly drained areas in a variety of parent materials ranging from sandy to clayey in composition.

Great groups of the Gleysolic order are differentiated by the presence or absence of organo-mineral Ah horizons, and of illuvial (Bt) horizons. Humic Gleysols have thick Ah and no Bt horizons; Gleysols have thin or no Ah horizons and no Bt horizons; and Luvic Gleysols have Btg horizons. Subgroups are differentiated on the basis of presence and/or type of B horizon as described by the Expert Committee on Soil Survey (1978).

Gleysolic soils occur throughout the province where water is retained in the soil profile for long periods. They occur in undrained depressions to level areas in subhumid regions, and on level to gently sloping terrain in humid regions. Hydrophytic vegetation is a feature of Gleysolic soils, but the indicator species vary from region to region. In the prairie and parkland areas, Gleysolic soils occur in marsh ecosystems. In the Boreal forest, Gleysolic soils occur in marshes and swamps (treed wetlands) and grade into Organic soils. Peaty surface layers generally occur on Gleysols in Boreal regions. All Gleysolic subgroups can be found in Alberta; however, those with podzolic B horizons occur predominantly in Alpine regions.

In general, Gleysolic soils are not considered to be sensitive to acidification because they are subject to high inputs of soil materials and solutes through runoff and subsurface flow of groundwater. They are, therefore, relatively rich in bases and nutrients and have a high capacity to neutralize acidity. Although Gleysolic soils can develop in a variety of parent materials, they have broad similarities in their chemical characteristics. They have medium to high contents of organic matter in their surface horizons. Cation exchange capacities are relatively high except in sandy Gleysols. Gleysols in Boreal regions are mainly slightly acid to neutral in reaction throughout the profile. In prairie regions, however, saline and alkaline Gleysols commonly occur in association with Chernozemic and Solonetzic soils. A review of Gleysolic soil data from throughout the province by Holowaychuk and Fessenden (1986) indicated that the overall range of pH was 4.6 to 7.7 in both surface and subsurface layers. The range of most pH values was 6.1 to 7.3 for surfaces, and 6.6 to 7.7 for subsurface layers. The CEC range is from less than 6 to about 40 $cmol(+)kg^{-1}$, and the base saturation can vary from less than 10% to 100% (Holowaychuk and Fessenden 1986). Some of these and other properties are demonstrated in the example of a representative Gleysolic soil profile described in Table 40.

Gleysolic soils have been mapped throughout the province, and account for a total of about 21,600 km^2 (Table 4). Those of significant areal extent occurring within regions covered by SIDMAP (Patterson and Peterson 1984) are listed in Table 41. In the prairie region, Gleysols in their native and undrained state are used for native

Table 40. Description of an Orthic Humic Gleysol - Codner series.[1,2]
(NE33-55-12-W5; poorly drained; glaciofluvial over lacustrine; coarse-loamy over fine-loamy)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
L-H	15-0	-	-	-	-	-	-
Ahg	0-15	very dark grayish brown (10YR 3/2m)	loam	strong, fine granular	very friable	-	-
Bg	15-37	yellowish brown (10YR 5/4m)	sandy loam	single grain	very friable	-	-
BCg	37-70	brown (10YR 4/3m)	loam	stratified	friable	-	-
Ckg	70+	brown (10YR 4/3m)	silty clay loam	stratified	friable	-	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
L-H	6.4	-	-	-	-	0.2	0.5	26.2	4.4	36.8	85	-	-	-	-
Ahg	6.8	-	0.31	2.8	9	0.5	0.1	12.9	2.7	15.0	100	-	42	47	11
Bg	7.0	-	0.04	0.5	12	0.1	0.2	10.8	3.5	12.4	100	-	69	19	12
BCg	6.9	-	-	-	-	0.1	0.3	12.5	4.2	16.2	100	-	34	46	20
Ckg	7.0	-	-	-	-	0.1	0.4	17.2	4.7	20.9	100	-	6	62	32

[1] Adapted from the original table in Peters (1981)

[2] See Table 9 for explanation of abbreviations and symbols.

Table 41. Major soil series of the Gleysolic order in the white and yellow land use areas.[1]

Soil Subgroup	Textural Family	Series	Mapped Area Sections	km²
Orthic Humic Gleysol	clayey	Goose	440	1140
	fine-loamy	Codner	246	637
Orthic Gleysol	clayey	Prestville	472	1223
Orthic Luvic Gleysol	clayey	Snipe	857	2220
	fine-loamy	Wanham	264	684
Undifferentiated	fine-loamy	Smoky	341	883
Other Subgroups[2]	-	-	-	-

[1] Adapted from the original tables in SIDMAP (Patterson and Peterson 1984)

[2] Although mapped, total series area is less than 100 sections.

hay production, rough grazing, or wildfowl habitat. Gleysols which tend to dry up in the spring are cultivated, while those with water levels which persist through the summer are increasingly being drained and cultivated for crop and hay production, or for pasture. Gleysols in Boreal forest regions are generally in their native state and are valued as wildlife habitat. The Peace River delta area in northern Alberta is a notable, large area of wetland ecosystems on Gleysolic soils. Because these soils are young, with some areas being continually replenished with calcareous sediments, the soils are considered to be relatively insensitive to inputs of acidic substances.

4.11 REGOSOLIC ORDER

Soils of the Regosolic order occur in association with most other mineral soil orders. They occur in all parts of the province but do not extend over large areas except in Alpine regions.

Regosolic soils are well to imperfectly drained mineral soils with no or very wet profile development. They lack a B horizon but may have an organic surface (LFH) horizon or a weakly developed organo-mineral Ah horizon. Regosolic soils reflect essentially the characteristics of the C horizons or of the parent materials from which they are formed. Soil forming processes have not had sufficient time to form soil horizons. Regosolic soils predominantly occur on more recently deposited sediments of fluvial, colluvial, and eolian origin. Two great groups in the Regosolic order are differentiated according to whether or not an Ah horizon of at least 10 cm thickness is present. The Regosol great group has only a C horizon; the Humic Regosol great group has an Ah-C horizon sequence. Further division into subgroups is based on presence of gleyed features and cumulic layers.

There may be various reasons for the weak pedogenetic development of Regosolic soils. They may have developed on very young geological materials such as river sediments (alluvium) or be found in unstable landscapes such as eroding slopes or active sand dunes. The greatest extent of Regosols is in high mountain areas where surface materials, mainly rock debris, are continually disrupted by colluvial processes and by frost action.

Regosolic soils are highly variable in their chemical and physical properties. Regosols on sand dunes and rock debris are unvegetated due not only to adverse climatic conditions but also to low fertility and water holding capacity. Regosols in alluvial landforms, however, are commonly highly fertile and support shrub and forest vegetation. An example of an Orthic Regosol located on a river terrace is given in Table 42. Regosols on eroding slopes and knolls occurring in association with Chernozemic soils support vegetation to varying degrees depending on degree of alkalinity and calcareousness, droughtiness, and other factors. The chemical characteristics of Regosols are generally similar to those of the soils and their parent materials with which they are associated.

Regosolic soils have been mapped throughout the province. In SIDMAP, only the Antelope series, an Orthic Regosol on sandy parent material, accounts for a relatively large area (400 sections, or 1040 km^2). The total area of Regosolic soils in Alberta is estimated to be about 7400 km^2 (Table 4).

Table 42. Description of Cumulic Regosol - Iosegun group.[1,2]
(NW6-69-21-W5; well drained; fluvial; fine-loamy to sandy)

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence	Roots	Boundary
L-H	5-0	black (10YR 2/1m)	-	-	-	-	-
Ah	0-5	very dark grayish brown (10YR 3/2m)	loam	single grain	friable	-	-
C1	5-20	brown to dark brown (10YR 4/3m)	loam	single grain	firm	-	-
C2	20-30	yellowish brown (10YR 5/4m)	sandy loam	single grain	firm	-	-
IIAhb	30-35	very dark grayish brown (10YR 3/2m)	sandy loam	single grain	friable	-	-
IIC1	35-70	yellowish brown (10YR 5/4m)	loam	single grain	firm	-	-
IIC2	70-100+	-	sand	single grain	loose	-	-

Horizon	pH (H_2O)	pH ($CaCl_2$)	N (%)	Organic C(%)	C/N	Exchangeable Cations (cmol(+)kg^{-1})				Total CEC (cmol(+)kg^{-1})	Base Sat. (%)	$CaCO_3$ Equiv. (%)	Sand (%)	Silt (%)	Clay (%)
						Na	K	Ca	Mg						
L-H	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ah	5.7	5.4	0.09	1.03	11	0.0	0.8	18.3	4.4	14.0	100	-	23	49	28
C1	5.6	5.3	0.06	0.76	11	0.2	0.6	13.0	3.9	10.7	100	-	40	40	20
C2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
IIAhb	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
IIC1	6.2	5.9	-	-	-	-	-	-	-	-	-	-	47	37	16
IIC2	7.7	6.4	-	-	-	-	-	-	-	-	-		96	4	0

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[1] Adapted from the original table in Knapik and Lindsay (1983)
[2] See Table 9 for explanation of abbreviations and symbols.

5. POTENTIAL IMPACTS OF ACID DEPOSITION ON ALBERTA SOILS

5.1 INTRODUCTION

Potential impacts of acid deposition on soils in Alberta were evaluated by three methods in this section. One method uses results of a recent soil sensitivity classification and mapping project in Alberta; summaries of soil sensitivity are provided for each of the soil orders. A second method involves qualitative descriptions of possible soil responses to acidic inputs. The third method explores the uses of models to simulate soil processes; that is, quantitative soil responses to acid deposition are estimated by applying a model developed in a different geographic area to selected soils in Alberta.

5.2 REVIEW OF APPROACHES TO EVALUATING EFFECTS OF ACID DEPOSITION ON SOILS

5.2.1 Introduction

A number of different methods has been used for assessing the impacts of acid deposition on soils. One of these rates soils according to the sensitivity to acid inputs of one or more of their properties. This is a qualitative approach based on known relationships among soil characteristics. It differs from an evaluation of the properties that influence sensitivity because limitations are imposed by availability and reliability of data on the soils of interest. Another approach to assessing impacts of acid deposition attempts to quantify soil responses to acid loadings. This is basically a modelling approach which, in its simplest form, consists of applying simple equations to simulate soil lime neutralization by acid inputs, or exchange of H^+ for base cations on the exchange complex.

Sensitivity rating schemes and models developed to simulate soil processes under conditions of external acid inputs are discussed in the following sections. While these approaches predict the consequences of acid deposition, another procedure more suitable for regulatory purposes is that of determining target loadings. The target loading is the maximum level of atmospheric deposition that results in no long-term, adverse ecological consequences (Working Group I 1983). It is based on dose-response concepts whereby a dose must be kept below some threshold value to avoid undesirable ecological changes. Dose-response relationships are difficult to determine for soils by experimental means; both sensitivity rating and modelling methods are needed, therefore, to help define target loadings for different soil types.

5.2.2 Soil Sensitivity Rating Schemes

5.2.2.1 Sensitivity rating approach. Sensitivity refers to the ease with which soils can be affected or influenced by acid deposition. Schemes for rating sensitivity of soils to airborne acids and acid forming substances have been developed for the purpose of grouping soil areas into sensitivity classes. The parameters used to estimate effects and determine sensitivity differ among rating systems. Some consider a single effect such as the change in base saturation in response to a given input of acidity. Others consider a number of effects either singly or collectively.

Some of the sensitivity rating systems developed in the United States and Canada have been reviewed by McFee (1983). These include the schemes of McFee (1980), Klopatek et al. (1980), Wang and Coote (1981), and Holowaychuk and Lindsay (1982). This latter system was developed for classifying and mapping the soils of the Sand River area in Alberta. All of these systems for classifying soil sensitivities were developed for broad regional mapping purposes and, therefore, had to use readily available data (such as that in soil survey reports) and had to ignore many inclusions in mapping units and variation within units. All are based on hypothetical inputs of acid in excess of those commonly experienced today and on idealized concepts of exchange reactions and base saturation-pH relationships. Soil sensitivity maps have their greatest usefulness in indicating which soils should be examined first in a search for acid deposition effects, but do not define areas which are actually being affected. Most of the schemes developed collectively consider pH reduction, drop in base saturation percentage, and release of Al to soil solution in determining the sensitivity rating. Klopatek et al. (1980) used similar criteria, but their rating system is specifically for sensitivity to "acidification." All of the schemes are conservative in that they assume an acid input which is a "worst case" situation, and class as sensitive any soils that might possibly show an effect in a rather long period such as 25 years. Most of them ignore acid consumption by weathering reactions, the recycling of bases by vegetation, the influence of accompanying basic cation inputs, and the influence of fertilizers and lime (McFee 1983).

None of the systems considers impacts other than those on pH and the exchange complex. For example, effects on organic matter turnover and on dynamics of major nutrients such as N, P, and S are not considered. This is because there is insufficient information on impacts of these properties for developing sensitivity criteria. All systems, however, are valuable in that they provide a first approximation of potential impacts on some properties, and they have been developed to identify specific soil types sensitive to acid deposition, as well as their locations.

5.2.2.2 Sensitivity rating system and mapping in Alberta. The classification and mapping of Alberta soils' sensitivity to acid deposition has recently been carried out by Holowaychuk and Fessenden (1986). Similar projects have been conducted in the other provinces and territories.

The general objective of the soil sensitivity rating project is to assess or predict the relative sensitivities of the soils of Alberta to possible effects from the deposition of acid or acidity-generating airborne pollutants and to estimate the relative potential of these soils to neutralize the incident acidity before it becomes a constituent of the soil effluent that could enter an aquatic ecosystem. The sensitivity rating project had the following specific goals:

1. to describe and show the distribution of soils in the province at a map scale of 1:2,000,000;
2. to estimate and map the relative sensitivity of soils in terms of their major soil chemical processes, namely acidification or decrease in pH, the decrease in base saturation and loss of cations through leaching, and the increased solubilization of toxic elements such as aluminum;

3. to estimate and map the potential of these soils to neutralize the incident acidity derived from atmospheric deposition; and
4. to document the various procedures used to categorize soils in terms of their sensitivity and acidity neutralizing potential.

Soils of the province were described by delineating major soil landscape units and indicating the properties of both dominant and sub-dominant soils in each map unit in tables. Because the classification and mapping is on a broad, regional base, it was necessary to ignore many inclusions in mapping units and variation within soils. Attributes of soils used to differentiate map units include taxonomic class, pH, texture, and kind of parent material. A more comprehensive characterization of soils is given by data presented in tabular form.

The criteria for rating the sensitivity of mineral soils to acid deposition are based on cation exchange capacity and pH as they influence the three target soil chemical processes indicated above. Criteria for Organic and Organic Cryosolic soils take the base content and alkalinity of soil water into account. Three ranges of cation exchange capacity are considered: low CEC, or <6 cmol(+)kg^{-1}; medium CEC, or 6-15 cmol(+)kg^{-1}, and high CEC or >15 cmol(+)kg^{-1}. The pH categories used are in increments of 0.5 units from <4.6 to >6.5 as outlined by the Expert Committee on Soil Survey (1983).

Soils of low pH and low CEC are considered to be highly sensitive to base loss and to Al solubilization. Soils of medium or high CEC, but with low pH, are also rated as highly susceptible to base loss and Al solubilization. Soils of medium or high CEC, and of intermediate pH (about 5.0 to 6.0) are moderately sensitive to base loss and Al solubilization. Soils of intermediate pH are most highly sensitive to acidification if the CEC is low; sensitivity decreases to moderate and low categories with increase in CEC. Sensitivity of each of these processes (acidification, base loss, and Al solubilization) to acid deposition is considered to be low in all soils with pH > 6.5. All soils are assessed for sensitivity of each of these three soil processes; an overall sensitivity rating is also estimated and indicated on maps. Criteria for capacity to neutralize acidity are based on sources of buffering which are related to CEC, base saturation, content of easily weatherable minerals, and other factors.

Further information about soil sensitivity ratings in Alberta can be found in Holowaychuk and Fessenden (1986). The summary provided in this section is intended as a general review of current work in this area, and serves to provide reference material for discussion regarding sensitivity ratings in the following sections.

5.2.3 Modelling Soil Responses to Acid Deposition

Models are formal expressions of the relationships between defined entities in physical or mathematical terms. Ecological research has a particular need for the use of models because of its concern with the multiple interactions of a wide variety of ecosystem components. Nearly all of these interactions are dynamic in the sense that they vary with time and are constantly changing. These interactions may frequently possess the characteristics of feedback, or the carrying back of some of the effects of a process to their source or to a preceding stage so as to strengthen or modify them. There is a need for use of models in ecological research in order to unravel the inherent complexity of ecological relationships and to simulate the long time scales characteristic of many of these interactions. Another valuable use of models is the integration and testing of compatibility of information already collected about a system. A model can be regarded as a synthesis of information about a system and subsequently can be used to locate information gaps, to formulate hypotheses for testing, to predict changes in system components, and ultimately to formulate plans and make management decisions.

Several models have been developed in recent years to describe various processes in soils. Some have been developed specifically to simulate and predict soil responses to acidic inputs. They vary from simple codes to complex components of more comprehensive ecosystem models. An example of a simple code is that of McFee et al. (1977) in which reduction in soil base saturation was calculated for given inputs of acidity which were assumed to completely replace bases on the exchange complex. Change in pH was then approximated from a curve of soil pH versus base saturation determined for soils in the area of study. The approach is simple, makes many assumptions, and ignores weathering and other acid neutralizing reactions, but provides a quick assessment of specific soils and enables comparisons to be made among them.

Soil process models which have been developed to describe acid deposition responses deal mainly with soil chemistry and do not attempt to represent other soil attributes such as organic matter decomposition, microbial dynamics, solute transport, and others. Most of them describe soil processes only and are not linked with other ecosystem components. However, numerous other models (i.e., not developed for acid deposition studies) do describe these other soil attributes, and they may be useful in analysing acid deposition effects on soils or for coupling with other models to enable examination of several soils and ecosystem components and their interactions. Some of the acid deposition-soil response models are codes built into other models, mainly aquatic acidification models. Various categories of models are summarized below, with emphasis on those developed for soil response to acid deposition.

1. Models of soil chemical properties in relation to acid deposition. Reuss (1980) developed a model based strictly on soil chemical properties to predict the distribution of ions between the solution and sorbed or exchangeable phases. The model can be used to simulate leaching of bases in noncalcareous soils and in both sulphate sorbing and non-sulphate sorbing soils. Further documentation of modelling soil chemical processes, and of linking these to plant systems and to surface and groundwater systems, has recently been provided by Reuss and Johnson (1986).

   Arp (1983) developed a model in which weathering and nutrient cycling were taken into consideration. Acid cation loss, base cation loss, change in base status, and time required to reach a specific base content can be predicted by the model.

   Bloom and Grigal (1985) described a simple, semi-empirical model for predicting changes in soil pH and base saturation resulting from acidic precipitation. Changes in soil reaction, base status, and soluble Al, over specified periods of time, can be predicted from the model. Bloom and Grigal (1985) argued that other numerical models developed to predict long-term effects of acid deposition on soil, such as those indicated above, require input of detailed data which is usually not available. Therefore, they developed a model which would be more appropriate for broad application by planning or regulatory agencies and which could make use of readily available data. Several assumptions are used in the model and management effects are not considered.

2. Lake and watershed acidification models incorporating soil process codes. The Integrated Lake-Watershed Acidification Study (ILWAS) Model was designed to determine the effects of acid deposition on the chemistry of natural water bodies. Included in the model are changes which occur in soils during movement of water from watersheds into lakes (Gherini et al. 1985). Soil processes which are represented include litterfall and decay, nutrient uptake, root respiration, CO_2 exchange, nitrification, anion adsorption, cation exchange, mineral weathering, and aluminum reactions. A somewhat simpler, empirical model, known as the Cation Denudation Rate Model, has been developed to investigate acid deposition impacts on aquatic systems in eastern Canada (Thompson 1982). The soil component in the model is a single, empirical factor which accounts for cation exchange. These two models are representative of those which have been developed for evaluating acid deposition impacts. The soil process models discussed in the previous section do not link with other ecosystem components but could be applied in this way as indicated, for example, by Arp (1983) and Reuss and Johnson (1986).

3. Geochemical models. These include models such as GEOCHEM (Sposito and Mattigod 1979), PHREEQE (Parkhurst et al. 1980), and others which calculate chemical equilibria, reactions, and chemical species in solutions. A number of these have been reviewed by Kincaid et al. (1984). GOECHEM has been used to predict the speciation of soil solutions affected by acid deposition (Sposito et al. 1980). All of these models may have application in studies of soil response to acid deposition and in coupling with other models for more comprehensive ecosystem response evaluations.

4. Biogeochemical models. The cycles of carbon, nitrogen, phosphorus, and sulphur are of particular importance in the soil. The PHOENIX model of dynamics of carbon and nitrogen in grassland soils has been described by McGill et al. (1981a). A model for sulphur, carbon, and nitrogen transformations in soil has been developed by Hunt et al. (1986). Other models of nutrient cycling in grassland and forest systems are available.

5. Soil genesis models. A simulation model for leaching and acidification processes in soils has recently been reported by Levine and Ciolkosz (1986). The model is used to simulate changes in soil properties over time and therefore may be suitable for evaluation of responses to long-term, low level inputs of acidity.

6. Nutrient uptake models. Several nutrient uptake models have now been developed, examples being those of Luxmoore et al. (1978), Nye (1979), and Barber (1984). These models are a necessary link in determining plant responses in relation to soil properties as influenced by acidic inputs.

7. Models of nutrient uptake coupled with soil water and solute transport. Several of these kinds of models have been reviewed by Kincaid et al. (1984). These are primarily unsaturated flow models but include codes for simulating water and solute uptake by plants.

8. Models of water and solute transport in unsaturated flow conditions. Numerous models of this type have been reviewed by Kincaid et al. (1984). The models describe either water and solute transport per se, or specifically describe migration of pollutants through soils and subsoils. The few codes which couple geochemical processes with solute transport are also reviewed by Kincaid et al. (1984).

Due to the complexity of the soil system, and because of the need to relate soil processes to other components of the ecosystem (particularly to growth of vegetation in terrestrial systems and to water chemistry and biota in aquatic systems), a modelling approach may well be most suitable for analysis of acid deposition impacts in Alberta. Mathematical simulation would aid in synthesis of available information, identification of information deficiencies, prediction of responses to given acidic inputs, planning and interpretation of research, and ultimately in planning regulatory, control, and remedial strategies.

Only models pertaining to the soils component of ecosystems are discussed above. The discussion serves mainly to describe and give examples of some soil-related models which have been developed. While some of these are specifically acid deposition response models, they may not be applicable to Alberta conditions and other models may, therefore, need to be evaluated for their applicability. The soils component is highly important in assessing total ecosystem impacts of acid deposition. It may also be the most complex component of a model, requiring considerable computational effort, as was found in development of the ILWAS model (Gherini et al. 1985). Therefore, it is necessary that a thorough review of modelling approaches and of specific models be undertaken prior to actually undertaking any modelling exercise.

To the greatest extent possible, a model for acid deposition impacts should be fairly simple so that, as indicated by Bloom and Grigal (1985), it can make use of readily available information such as that in soil survey reports. When impacts on a variety of soils occur within a large geographic area need to be considered, a model would be most useful when coupled with a geographic information system (GIS) containing spatial and thematic baseline soils data. The acid deposition responses of all soils described within the GIS could then be determined by application of the soil response model to the data in the GIS. The products of such an exercise could be plots of response over time, calculations of target loadings, or other forms of derivative data. A first step for soils of Alberta may be to quantitatively determine responses of soils and soil mapping units of the sensitivity map produced by Holowaychuk and Fessenden (1986). A model, provided its performance has been verified and validated, could be used to check the essentially qualitative interpretations of the soil sensitivity map of Alberta. Following this procedure, derivation of target loadings or of other desired data could be easily carried out.

5.3 APPLICATION OF SENSITIVITY RATING AND MODELLING APPROACHES TO ALBERTA SOILS

5.3.1 Sensitivity Rating Methodology

The rating of Alberta soils according to sensitivity to pH reduction, base depletion, and increase in soluble Al^{3+} is the objective of a concurrent project (Holowaychuck and Fessenden 1986). A brief overview of this project was provided in Section 5.2.2.2. Sensitivity ratings by soil order are summarized from this project and are presented in the following sections.

5.3.2 Modelling Methodology - Application of Bloom and Grigal (1985) Model.

5.3.2.1 Description of the model. The model is described by Bloom and Grigal (1985). The main features of the model are presented here, but the paper should be referred to for a full description.

The model is described as semiempirical, and was developed for estimation of the long-term effects of acidic deposition on nonagricultural soils. Agricultural soils were excluded because of the much greater effects of management practices such as fertilization and liming as compared to acidic deposition. It is used in this report, however, as an exploratory tool with agricultural soils in which management practices are minimal (as in rangelands) as well as with some cultivated soils. The model simulates changes in exchangeable bases, soil pH, and soil solution Al with time. As with other models discussed previously, the assumptions used are conservative, and the rates of change that are calculated are maximal rates (Bloom and Grigal 1985).

5.3.2.2 Assumptions. The assumptions used in the model, condensed from Bloom and Grigal (1985), are as follows:

1. Sulphate is not adsorbed by the soil and is treated as a mobile anion;
2. The depth of soil affected by acidic inputs is 25 cm. This is the depth in forest soils within which most plant roots are located and which is most important for forest tree nutrition;

3. The current measured properties of the soils reflect a steady state condition. The pH and base status in an undisturbed soil represent an integration of rates of soil weathering, biocycling, additions of organic acids, and leaching of bases from the surface soil. Addition of acidic deposition disturbs the steady state. This is the main reason the model is not applicable to soils under cultivation, under regenerating forest stands, or under other disturbed situations;
4. The acidic deposition reacts completely with the top 25 cm of the soil;
5. The effective acidity in rain and snow equals H^+ plus NH^{4+} minus NO_3^-;
6. The volume of water flowing downward from the top 25 cm soil layer is equal to precipitation minus evapotranspiration. This also assumes that plants obtain all their water from the top 25 cm of soil;
7. Soil solution pH can be calculated from the equation,

$$pH + 1/2 \log [Ca^{2+} + Mg^{2+}] = constant \qquad [36]$$

In Minnesota, $[Ca^{2+} + Mg^{2+}]$ is estimated to be 2×10^{-4} mol L^{-1} in forest soils. The soil solution pH is, therefore, 0.8 units greater than soil pH measured in 0.01 mol L^{-1} $CaCl_2$.

8. The partial pressure of CO_2 (P_{CO_2}) in soil air is 0.005 atmospheres (0.0005 MPa);
9. The chemical activity of Al^{3+} in the soil solution of surface soils can be calculated from the equation,

$$\log (Al^{3+}) = 2.60 - 1.66 \, pH; \qquad [37]$$

10. The rate of mineral weathering does not increase with a decrease in pH;
11. The pH of soil solutions is related to the base saturation by a form of the extended Henderson-Hasselbach equation in which,

$$pH = pKa + n\log[BS/(1-BS)] \qquad [38]$$

where pKa is the apparent acidity constant for a soil, n is an empirical constant and BS is the base saturation.

All the assumptions of the Bloom-Grigal model apply in simulations on Alberta soils. Cases in which non-steady state soils were selected for application of the model represent hypothetical situations. Weathering was not considered in the model (i.e., the value for the weathering parameter was set at zero).

5.3.2.3 Capabilities and limitations. Bloom and Grigal (1985) found that results of simulations for Minnesota soils were comparable in pH, base saturation, and soluble Al values to actual data for acidified soils in eastern United States and in Germany. The computations were rapidly carried out on a microcomputer using a program written in

BASIC. Due to the assumptions made, simulations result in overestimation of changes in pH, base saturation, and solution Al. This can be either an advantage or a disadvantage, depending on how the results are to be used. Graphical display of change in pH, base saturation, or Al concentration over time enables quick comparison of different soils.

Bloom and Grigal (1985) indicated that the model is especially well suited for calculation of the response of soils that are buffered by cation exchange. Generally, these are soils in the pH (H_2O) range of 4.0 to 5.0, but many also have pH values >5.0. At pH (H_2O) values of 4.0-2.8, soils are buffered by dissolution of Al^{3+}, and the magnitude of pH and base saturation changes will be much less than for cation-exchange buffered soils.

Limitations of the model relate to the assumptions made to keep it simple and to enable its use of easily obtainable data inputs. Other models indicated in previous sections have the same limitations. For example, use of annual precipitation and evapotranspiration data does not take into consideration the effects of variations such as average precipitation event input as compared to either prolonged rainfall or to high input rates in storm events. Bloom and Grigal (1985) indicated, however, that where surface runoff data is available, it can be subtracted from precipitation. A modification of the model which uses monthly data inputs is also in preparation (P. Bloom and D. Grigal, personal communication, 1985).

Other limitations were discussed by Bloom and Grigal (1985). They suggested that more work is required to determine if the pH-Al relationship in assumption 9 (above) is applicable to a wide range of soils. They also noted that effects of management of forest soils should to be taken into account.

There are some limitations in applying the model to soils of Alberta. Many forest soils in Alberta have surface pH (H_2O) values in excess of 5.0 where mineral weathering as well as cation exchange contributes to buffering. Therefore, application of the model without input of weathering data will overestimate changes to a greater degree than it would for soils in the CEC buffering range of pH (H_2O) 5.0-4.0.

The model is not suitable for soils which are not in a steady state, cultivated soils being an example. A method for assessing representative soils from all major orders was necessary in this report. It was decided that the model of Bloom and Grigal would be used as an exploratory tool to examine these soils, but at all times the assumptions which are violated would be recognized.

A considerable proportion of Alberta's land area consists of organic soils. The model of Bloom and Grigal was developed for mineral soils and it assumes that the organic portion of them is unaffected by acidic inputs. It is not applicable to organic soils and alternative means of assessing impacts on these soils need to be developed. The basic structure of the model may be applicable, but the pH - base saturation - [Ca + Mg] - Al relationship for calculations may be very different for organic soils than for mineral soils. The effect of acidic deposition on the properties of organic soils themselves, as well as on their associated waters, is a concern in Alberta and considerably more research will be required to determine these impacts.

5.3.2.4 Soils used in simulations. Thirteen of the pedons described in Section 4 have been selected for acid deposition simulations using the Bloom-Grigel model. Most of the pedons are representative of highly and moderately sensitive members of the Chernozemic, Solonetzic, Luvisolic, and Brunisolic orders. Most Chernozemic and Solonetzic soils are under cultivation. An attempt was made, therefore, to select data from the literature for pedons which had been sampled in native sites. As noted above, the Bloom-Grigal model was developed for evaluation of forest soils in a steady state and application to agricultural soils violates this assumption. However, it is used here as an exploratory tool with the realization that the results may not be as realistic as they would be for forest soils. Representative pedons of four Chernozemic soils, two Solonetzic soils, five Luvisolic soils, and two Brunisolic soils were selected. The specific pedons are indicated in the appropriate sections which follow.

The 13 pedons were selected to represent the mineral soil orders of largest areal extent in the province. This small number was considered to be sufficient for an initial modelling exercise and for demonstrating potential impacts in the major soil orders.

5.3.2.5 Data inputs. The input data and their sources or derivation are indicated below. All the assumptions of the model (Section 5.3.2.2) apply to simulations with Alberta soils. Some additional assumptions pertaining to data inputs to the model were made as indicated below.

1. Annual precipitation - Long-term precipitation data were obtained from summary reports of the Atmospheric Environment Service (1980). Data for climate stations nearest to the locations of the pedons used in the simulations were used. No effort was made to estimate surface runoff for correction of the total precipitation input.
2. Annual evapotranspiration - Averaged data from the Atlas of Alberta (Government and University of Alberta 1969) were used.
3. Acidity of wetfall - Canadian Network for Sampling Precipitation (CANSAP) data from five stations in Alberta and from stations near the provincial border in Saskatchewan and British Columbia were examined. The pH of precipitation reported on a monthly basis during 1980 ranged from about 4.5 at the Cree Lake, Saskatchewan station to about 7.3 at the Lethbridge station. In general, the pH of precipitation in western Canada and the western United States is somewhat higher than that of eastern provinces and states (Working Group I 1983). It was decided to take pH 5 as a crude estimate of an average low value for the province. This also is the weighted mean pH for the year 1980 in northern Alberta (Working Group I 1983). This figure was used in simulations of all of the soils.
4. NH_4 in wetfall - CANSAP data for Coronation, Lethbridge, and Kindersley stations indicated an average NH_4 level of about 300 $\mu mol\ L^{-1}$. CANSAP stations in western and northern areas (Rocky Mountain House, Grande Prairie, Fort McMurray, Cree Lake, and Fort St. John) had average NH_4 values of 10-20 $\mu mol\ L^{-1}$. These levels were used for soils from corresponding areas.

5. NO_3 in wetfall - CANSAP data for the southern stations had average NO_3 values of about 40 μmol L^{-1} while those of northern stations ranged from 10-36 μmol L^{-1}. The excess of NO_3 over NH_4 was sufficient to negate acidic input in precipitation (i.e., $H^+ + NH^{4+} - NO_3^-$ became negative). The calculated averages could be erroneous because data from some months were missing; moreover, the levels of NO_3 and NH_4 from month to month were highly variable. It was decided, therefore, to equate the data inputs for NO_3 and NH_4 for each case, and to assume H^+ to be the sole source of acidity in wetfall.
6. Ratio of dryfall acidity to wetfall acidity - Research into SO_2 sorption by soils, such as that of Nyborg et al. (1980) suggests that dryfall acidity can exceed wetfall acidity by several times. A ratio of 4.8 for central Alberta has been reported by Caiazza et al. (1978). The ratio of 0.2 for Minnesota (Bloom and Grigal 1983), therefore, does not appear to be applicable in Alberta. Bloom and Grigal (1985) used the estimate of 0.2 for simulations throughout their study area. There is considerable interest in Alberta, however, in assessing impacts at varying proximities to the atmospheric SO_2 sources because there is evidence for much higher dryfall acidity near sources than at some distance from them. Ratios were therefore calculated on the basis of total loadings of acid forming substances selected as follows:
    a. Low deposition: 0.1 kmol(H^+)ha^{-1}

       0.1 kmol(H^+)ha^{-1} is equivalent to 16 kg S ha^{-1} (3.2 kg SO_2 ha^{-1}) assuming that 1 kmol SO_2, if completely converted to H_2SO_4, would generate 2 kmol H^+. This figure is similar in magnitude to the 0.04 kmol ha^{-1} (equivalent to 2 kg ha^{-1} of $CaCO_3$ neutralizing capacity) indicated by Sanderson (1984) as the annual contribution in Alberta to soil acidity by atmospheric deposition during 1977-1979. It is also similar to the 3 kg S ha^{-1} (or 0.19 kmol(H^+)ha^{-1} equivalent) estimate of annual total S deposition at remote points in northeastern Alberta and northern Saskatchewan (Shewchuk et al. 1981).
    b. Medium deposition: 1 kmol(H^+)ha^{-1}

       1 kmol(H^+)ha^{-1} is equivalent to 16 kg S ha^{-1} (32 kg SO_2 ha^{-1} or to 7 kg N ha^{-1} (9 kg $NH_4^+ ha^{-1}$), assuming that all the SO_2 or NH_4^+ generate acidity. The S deposition rate is close to the level of 20 kg S ha^{-1} y^{-1} assumed by Hoyt et al. (1981) in projecting the effects of soil acidity of S deposited on land near emitters.
    c. High deposition: 3 kmol(H^+)ha^{-1}

       3 kmol(H^+)ha^{-1} is equivalent to 48 kg S ha^{-1} (96 kg SO_2 ha^{-1}) or to 21 kg N ha^{-1} (27 kg $NH_4^+ ha^{-1}$). This level approaches the maximum amounts of SO_2-S sorbed by bare soil surfaces in pots set out downwind and nearby SO_2 emitters in Alberta (Nyborg et al. 1980). It is also of a similar magnitude to the N fertilization rate (22.4 kg N ha^{-1}) used by Hoyt et al. (1981) to forecast effects of fertilization on soil acidity in Alberta.

A loading of 0.1 kmol(H^+)ha^{-1} is approximately equivalent to a ratio of 1:1 (wetfall:dryfall ratio) at a wetfall pH of 5; a loading of 1 kmol (H^+)ha^{-1} is equivalent to a ratio of 20:1; and a loading of 3 kmol (H^+)ha^{-1} is equivalent to a ratio of 60:1. The 60:1 ratio and a ratio of 10:1, selected as intermediate to 1:1 and 20:1, were used in only one simulation to demonstrate a wide range of impacts.

7. Soil pH - The pH documented for soils in earlier soil survey reports was generally obtained by the soil paste method. The difference between pH(paste) and pH($CaCl_2$) is commonly considered to be about 0.5 units for Alberta soils. Therefore, 0.5 was subtracted from pH(paste) values for model inputs. Otherwise, pH($CaCl_2$) values as reported for pedons were used. The pH values, moreover, were weighted arithmetic means for the top 25 cm of soil. A dry bulk density of 1.3 Mg m^{-3} was assumed in calculations of the weighted means.
8. Sum of bases in soil - All values for exchangeable bases were obtained by the ammonium acetate extraction method. Total bases in kmol(+)ha^{-1} were calculated for the 25 cm surface layer in the same way as pH.
9. Cation exchange capacity - Bloom and Grigal (1985) indicated that this input consists of the sum of bases plus $BaCl_2$-triethanolamine titratable acidity. Since data for titratable acidity are not generally available for Alberta soils, total CEC values obtained by the buffered (pH7) ammonium acetate method were used in the simulations.
10. Partial pressure of CO_2 in the soil atmosphere - Little data for P_{CO_2} is available, and because P_{CO_2} is quite variable, the value of 0.005 atmosphere used by Bloom and Grigal (1985) was also used in this project.
11. Increment of time between reported values - 50 years was selected as the interval for output of simulation results.
12. Length of simulation period - 500 years was selected.
13. Activity coefficients of Al^{3+} and $Al(OH)^{2+}$ - The values of 0.82 and 0.92, respectively, as already entered into the program by Bloom and Grigal (1985), were used.
14. Henderson-Hasselbach equation constants - The values of pKa and n in the extended Henderson-Hasselbach equation (equation 38, Section 5.3.2.2) differ for different soils. It was assumed that these constants would be similar for soils of the same order, but may differ between orders. Data for pH and base saturation were collected from a number of pedons sampled during recent soil surveys. The regression of pH on log (BS/1-BS) was calculated and plotted (Figures 6 and 7). The values for pKa and n, and their correlation value and level of significance are indicated in Table 43.

Correlations for Luvisolic and Solonetzic soils were relatively high as compared with those for Chernozemic and Brunisolic soils. Bloom and Grigal (1985) obtained an R^2 of 0.63 for a regression, yielding pKa = 4.96 and n = 0.797. The results suggested that more research is required in determining the variation in the relationship of pH and BS and in elucidating the factors responsible for the variation.

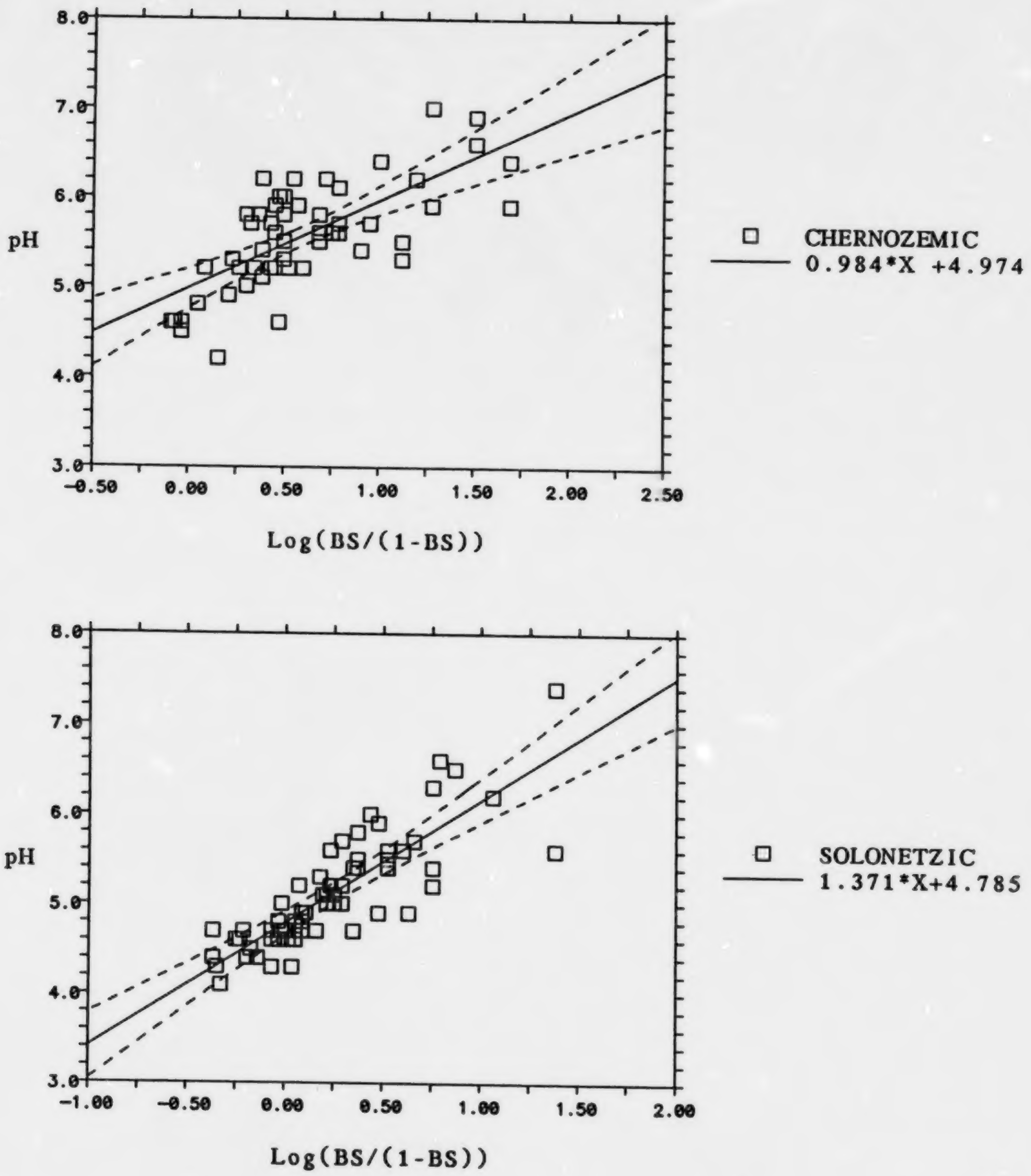

Figure 6. Regression of pH on log (BS/1-BS) for Chernozemic and Solonetzic soils in Alberta.

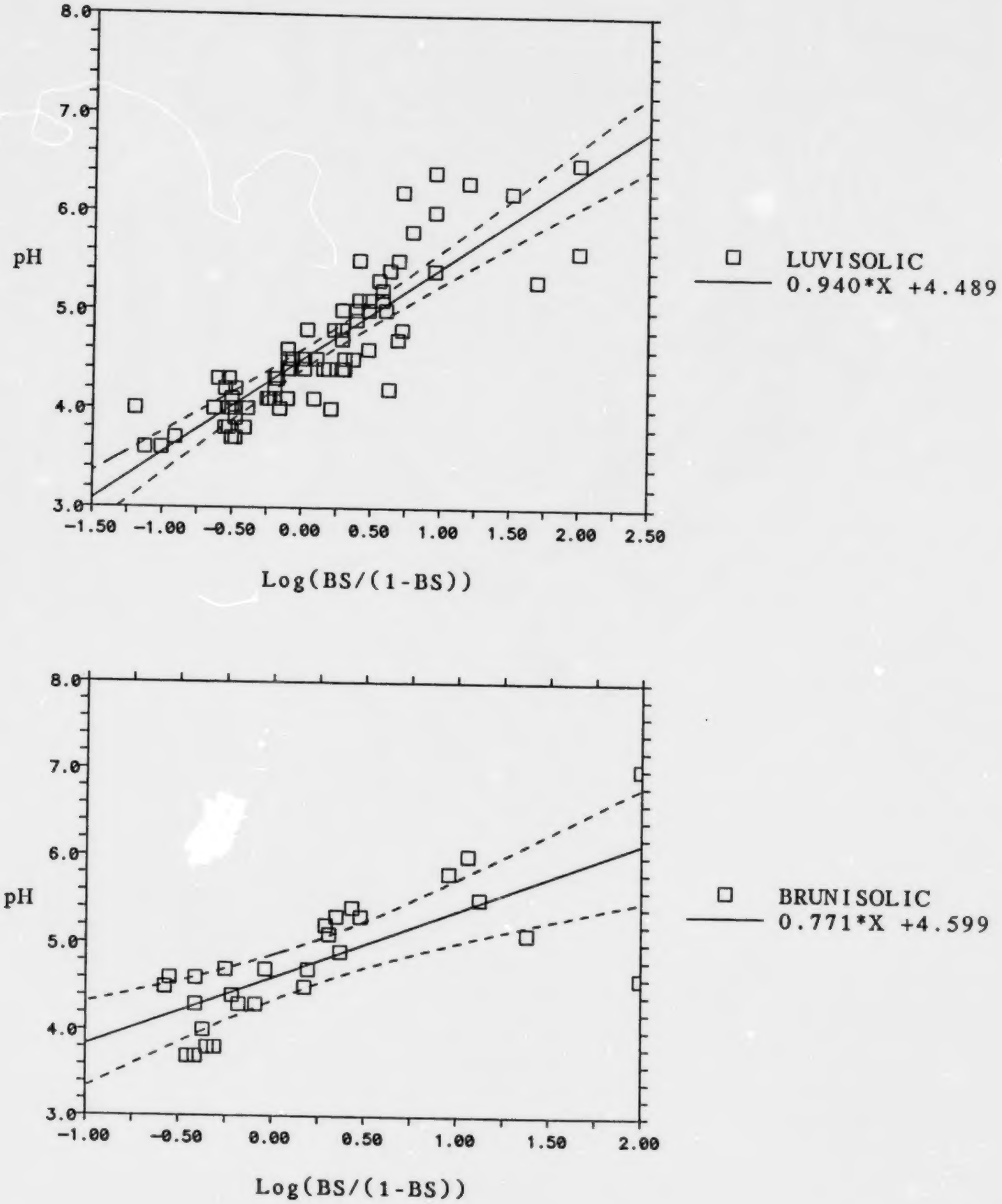

Figure 7. Regression of pH on log (BS/1-BS) for Luvisolic and Brunisolic soils in Alberta.

Table 43. pKa and n values for different soil orders calculated from the equation $pH = pKa + n\log(BS/1-BS)$.

Soil Order	N	pKa	n	R^2
Chernozemic	56	4.974	0.954	0.51***
Solonetzic	62	4.785	1.371	0.70***
Luvisolic	78	4.489	0.940	0.74***
Brunisolic	28	4.599	0.771	0.50***

***Significant at the 0.001 level.

The starting parameters for soils used in simulations are given in Tables 44 and 45. Along with input data described above, the soil subgroups and series are indicated. Each of the series was described previously in a table in Section 4. The total acid input, calculated from wetfall acidity and the dryfall:wetfall ratio, is also provided in Tables 44 and 45 in terms of H^+ input and S and SO_2 equivalent inputs. The S and SO_2 equivalents are provided to facilitate comparison with deposition data reported elsewhere in the literature.

5.3.2.6 Computations and data outputs. The program for microcomputer operation of the model was obtained on a diskette directly from the authors. The model was not altered in any way. Computations were made for changes in soil properties occurring on an annual basis.

Output data for each time interval include: (1) year; (2) pH of soil; (3) acid input; (4) acid output; (5) protonation; (6) change in pH; (7) base saturation; (8) sum of bases; (9) bases lost; and (10) soil solution Al. The output of major interest consists of the changed values of soil pH, base saturation, and Al. The annual loss of bases is calculated by:

$$S = I - A - C \tag{39}$$

where S is the sum of bases lost, I is the effective acidity in the precipitation plus dryfall, A is the acid leached out of the top 25 cm of soil, and C is the decrease in bicarbonate weathering due to the decrease in soil solution pH. A new sum of bases is calculated each year by subtracting the annual loss of bases. The new pH is calculated from the extended Henderson-Hasselbach equation. Al^{3+} in solution is calculated from the equation in assumption 9 in Section 5.3.2.2 above (Bloom and Grigal 1985). These data were transferred to a data management and statistics program on a mini computer and plots of pH, BS, and Al versus time were then generated.

5.4 CHERNOZEMIC SOIL IMPACTS

5.4.1 Sensitivity Ratings

The development and general properties of Chernozemic soils in Alberta are reviewed in Section 4.5. Holowaychuk and Fessenden (1986) have identified the following Chernozemic soil types as being sensitive to acid deposition: sandy, and some coarse loamy, Orthic Brown, Rego Brown, Orthic Dark Brown, Rego Dark Brown, Orthic Black, Rego Black, and Eluviated Black. A small area of Dark Brown soils in the Cypress Hills was indicated as being moderately sensitive.

The area of Brown Chernozemic soils is about 34,306 km²; about 5534 km² (16%) are considered to be sensitive in some way to acidic deposition (Holowaychuk and Fessenden 1986). These soils are predominantly slightly acid to mildly alkaline Brown, Regosolic Brown, and Regosol sandy and coarse-loamy soils on weakly to moderately calcareous eolian and glaciofluvial parent materials. Dark Brown Chernozemic soils occupy 40,418 km²; of this area, 5487 km² (14%) are considered to be highly sensitive to acid deposition. As with Brown soils, sandy and coarse-loamy types are the most sensitive. Of the 60,353 km² of Black Chernozemic soils, 2641 km² (4%) are considered to

Table 44. Starting parameters for Chernozemic and Solonetzic soil profiles selected to determine response to acidic deposition according to the Bloom and Grigal model.

Soil Subgroup	Orthic Brown	Orthic Dark Brown	Orthic Black	Orthic Dark Gray	Black Solodized Solonetz	Dark Brown Solod
Soil Series	Cavendish	Cradduck	Peace Hills	Redwater	Camrose	Brownfield
Annual Precipitation (cm)	35	42	49	49	45	45
Annual Evapotranspiration (cm)	30	40	40	40	40	35
Years of Iteration	500	500	500	500	500	500
Increment of Years	50	50	50	50	50	50
pH of Rainfall	5.0	5.0	5.0	5.0	5.0	5.0
NH_4 of Rainfall (μ mol L^{-1})	30	30	20	20	30	30
NO_3 of Rainfall (μ mol L^{-1})	30	30	20	20	30	30
Dryfall Correction Factor	1, 20	1, 20	1,10,20,60	1, 20	1, 20	1, 20
pH ($CaCl_2$) of Soil	6.0	6.4	6.0	6.2	4.8	4.9
Total Bases in Soil (kmol(+)ha^{-1})	231	558	175	284	497	426
CEC of Soil (kmol(+)ha^{-1})	263	724	299	319	949	579
Base Saturation (%)	90	77	59	89	52	74
CO_2 Partial Pressure (atm)	0.005	0.005	0.005	0.005	0.005	0.005
Activity Coefficient of Al^{3+}	0.82	0.82	0.82	0.82	0.82	0.82
Activity Coefficient of Al^{2+}	0.92	0.92	0.92	0.92	0.92	0.92
pKa Value	4.974	4.974	4.974	4.974	4.785	4.785
n Value	0.984	0.984	0.984	0.984	1.371	1.371
Total H^+ Input (kmol ha^{-1})[1]	0.07, 0.74	0.08, 0.8	0.10, 0.54, 1.03, 3.00	0.10, 1.03	0.09, 0.95	0.09, 0.95
Total Equivalent S Input (kg ha^{-1})	1.1, 11.8	1.3, 14.1	1.6, 8.6, 16.5, 48.0	1.6, 16.5	1.4, 15.2	1.4, 15.2
Total Equivalent SO_2 Input (kg ha^{-1})	2.2, 23.7	2.6, 28.2	3.2, 17.2, 33.0, 96.0	3.2, 33.0	2.8, 30.4	2.8, 30.4

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[1] Values for H, S, and SO_2 correspond to Dryfall Correction Factor. For example, at factor of 1 for Cavendish, dryfall and wetfall each contribute 0.035 kmol (H)ha-1 for a total of 0.07 kmol (H)ha-1. The factor of 20 yields 20(0.035) + 0.035 - 0.74 kmol (H)ha-1. Multiplication factors for S and SO2 are 16 and 32, respectively.

Table 45. Starting parameters for Luvisolic and Brunisolic soil profiles selected to determine response to acidic deposition according to the Bloom and Grigal model.

Soil Subgroup	Dark Gray Luvisol	Orthic Gray Luvisol	Orthic Gray Luvisol	Brunisolic Gray Luvisol	Orthic Gray Luvisol	Eluviated Dystric Brunisol	Eluviated Dystric Brunisol
Soil Series	Leith	Culp	Breton	Nosehill	Tom Hill	Firebag	Robb
Annual Precipitation (cm)	38	55	55	55	55	41	60
Annual Evapotranspiration (cm)	40	40	45	40	40	35	40
Years of Iteration	500	500	500	500	500	500	500
Increment of Years	50	50	50	50	50	50	50
pH of Rainfall	5.0	5.0	5.0	5.0	5.0	5.0	5.0
NH_4 of Rainfall (μ mol L^{-1})	20	20	20	20	20	10	20
NO_3 of Rainfall (μ mol L^{-1})	20	20	20	20	20	10	20
Dryfall Correction Factor	1, 20	1, 20	1, 20	1, 20	1, 20	1, 20	1, 20
pH ($CaCl_2$) of Soil	5.9	5.8	5.6	4.4	5.4	5.1	4.2
Total Bases in Soil (kmol(+)ha^{-1})	358	170	346	242	296	9	76
CEC of Soil (kmol(+)ha^{-1})	403	195	444	397	328	29	626
Base Saturation (%)	89	87	80	61	90	31	12
CO_2 Partial Pressure (atm)	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Activity Coefficient of Al^{3+}	0.82	0.82	0.82	0.82	0.82	0.82	0.82
Activity Coefficient of Al^{2+}	0.92	0.92	0.92	0.92	0.92	0.92	0.92
pKa Value	4.489	4.489	4.489	4.489	4.489	4.599	4.599
n Value	0.940	0.940	0.940	0.940	0.940	0.771	0.771
Total H^+ Input (kmol ha^{-1})[1]	0.08, 0.80	0.11, 1.16	0.11, 1.16	0.11, 1.16	0.11,1.16	0.08, 0.86	0.12, 1.26
Total Equivalent S Input (kg ha^{-1})	1.3, 12.8	1.8, 18.6	1.8, 18.6	1.8, 18.6	1.8, 18.6	1.3, 13.8	1.9, 20.2
Total Equivalent SO_2 Input (kg ha^{-1})	2.6, 25.6	3.6, 37.2	3.6, 37.2	3.6, 37.2	3.6, 37.2	2.6, 27.6	3.8, 40.4

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[1] See footnote of Table 44.

be highly sensitive, while 235 km^2 (<1%) are considered to be moderately sensitive. The sensitive soils are predominantly slightly acid to neutral, coarse-loamy Black soils on moderately calcareous glaciofluvial materials. There are 6848 km^2 of Dark Gray Chernozemic soils; of these, few are considered to be highly sensitive but 3578 km^2 (52%) are considered to be moderately sensitive. These soils are dominantly medium to slightly acid (pH 5.6 - 6.5) Dark Gray, with some Dark Gray Luvisols and Gray Luvisols on weakly to moderately calcareous clayey glaciolacustrine materials.

5.4.2 Model Predictions

The model of Bloom and Grigal (1985) was used to simulate responses of four Chernozemic soils selected to represent different great groups and different degrees of sensitivity to acid deposition. These are the Cavendish, Cradduck, Peace Hills and Redwater series which were described in Tables 9, 10, 11, and 13 in Section 4.5.8. Results of simulations are shown in Figures 8 to 10. Four soils with the indicated property and acid input are depicted in each of these figures.

At the lowest acid input level (about 0.1 kmol (H^+) ha^{-1} y^{-1} or dryfall:wetfall (D:W) ratio of 1), there is little change in pH, BS, or Al over time (Figures 8 to 10). Each of these parameters changes slightly; after 100 years of deposition the changes appear to be insignificant. With acid input of 1 kmol(H^+) ha^{-1} y^{-1} (Figure 8), pH drops significantly over time. The effect is greatest in the sandy Cavendish, Peace Hills, and Redwater series. In 100 years the pH of the fine-loamy Cradduck series drops only about 0.2 units. The others drop to about 5.5-5.8 from the original 6.0-6.2. The Cradduck and Redwater pH values diminish steadily with time while the Peace Hills values drop rapidly after 200 years and the Cavendish curve drops more rapidly after about 300 years. The slopes of curves of BS versus time show that the sandy soils have higher rates of BS decline than the fine loamy Cradduck series (Figure 9). The Peace Hills soil has low BS to begin with and loses about one-half of its bases in 100 years. Losses in soils of higher initial BS values are not as drastic on a proportional basis. The sandiest soils (Peace Hills and Cavendish) eventually become completely unsaturated in the time frame of the simulation (500 years). Parallel responses occur in Al values (Figure 10). An Al concentration of 10 μmol L^{-1} (10 μM) is considered to be a generally low limit for toxicity to trees (Bloom and Grigal 1985). This level is attained in about 200 years in the Peace Hills soil, 400 years in the Cavendish soil, and is not attained in the other soils.

Data are presented in a different manner in Figures 11 and 12 to demonstrate the effects of four different acid input levels on pH, base saturation, and Al concentrations. Only the Peace Hills soil was selected to demonstrate its response at the additional acid input levels of 0.5 and 3 kmol(H^+) ha^{-1} y^{-1}, corresponding to D:W=10 and D:W=60. The acid input of 3 kmol(H^+) ha^{-1} y^{-1} simulates possible S deposition levels near emitters and is similar to a moderate fertilization rate. The results for 0.5 kmol(H^+) ha^{-1} y^{-1}, as expected, are intermediate to the levels of 0.1 and 1 kmol(H^+) ha^{-1} y^{-1} discussed previously. A much more rapid change in properties occurs with input of 3 kmol(H^+) ha^{-1} y^{-1}. The pH drops from 6.0 to about 5.0 in 50 years, and to a minimum level of just above 3.0 in 100 years. Base saturation similarly drops drastically within 100 years. The 10 μM Al level is reached within 80 years.

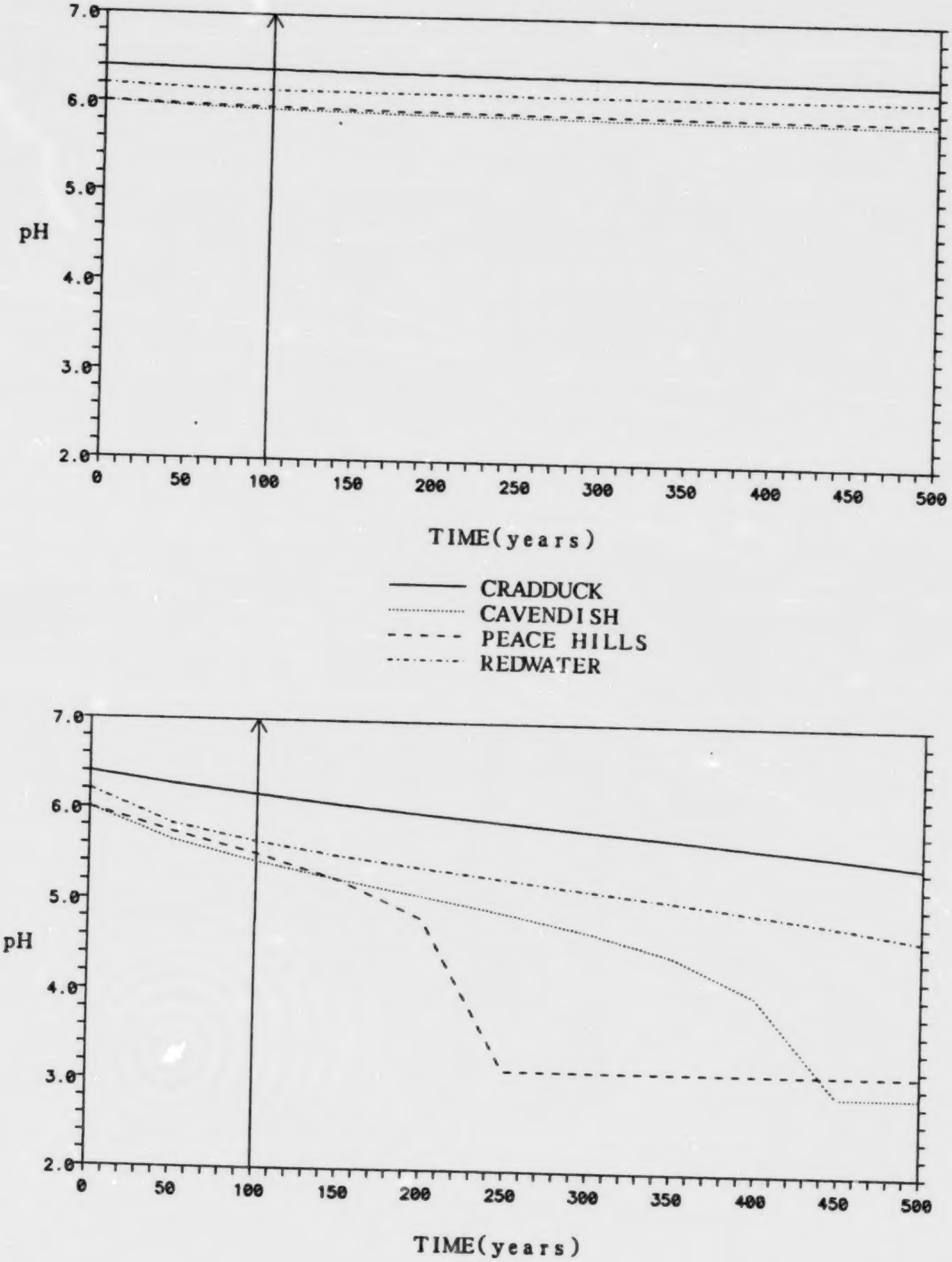


Figure 8. Model predictions for pH change in four Chernozemic soils having acid deposition inputs of approximately 0.1 (top) and 1 (bottom) kmol(H^+) ha^{-1} y^{-1}.

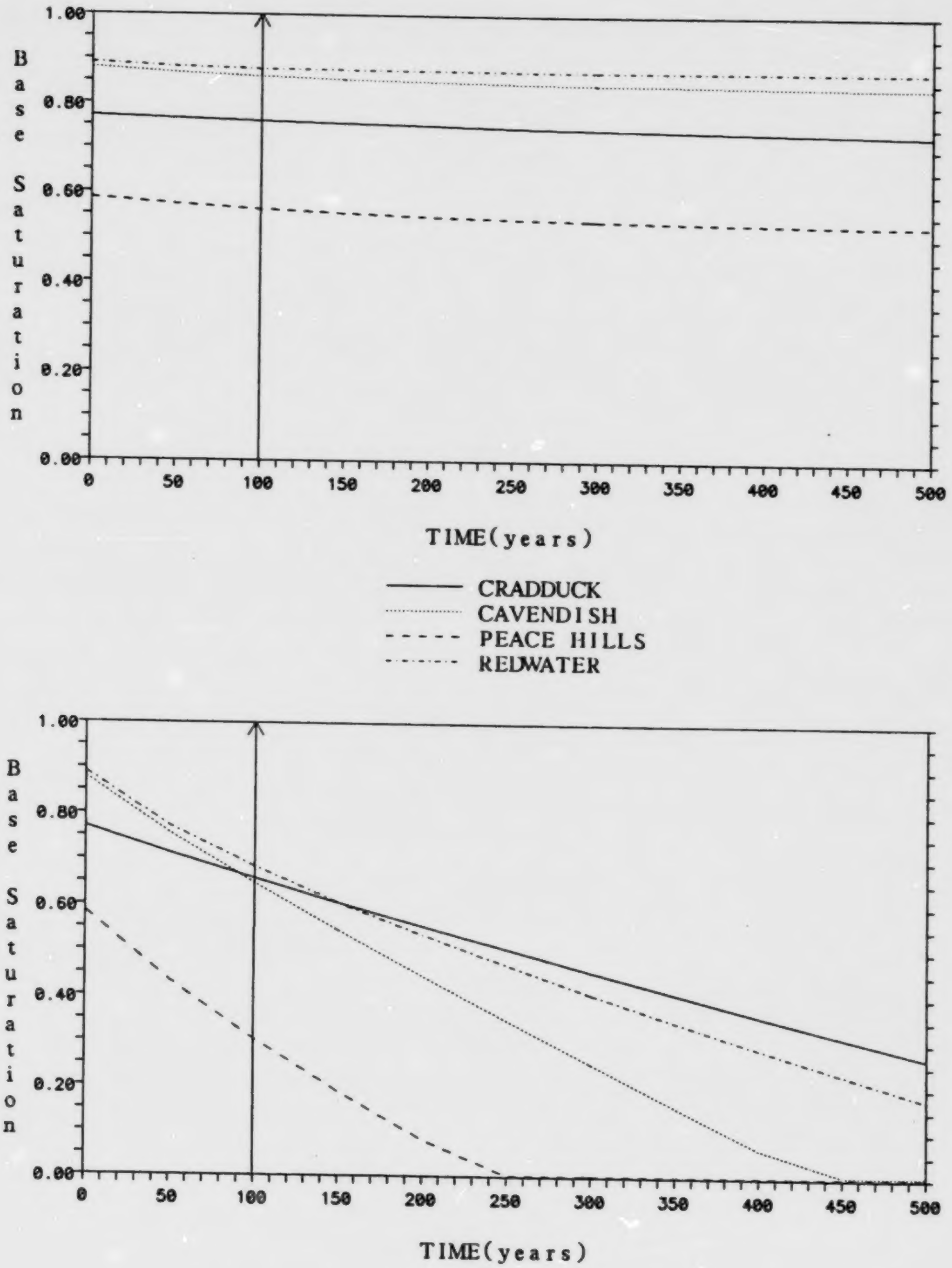


Figure 9. Model predictions for change in base saturation in four Chernozemic soils having acid deposition inputs of approximately 0.1 (top) and 1 (bottom) kmol(H^+) ha^{-1} y^{-1}.

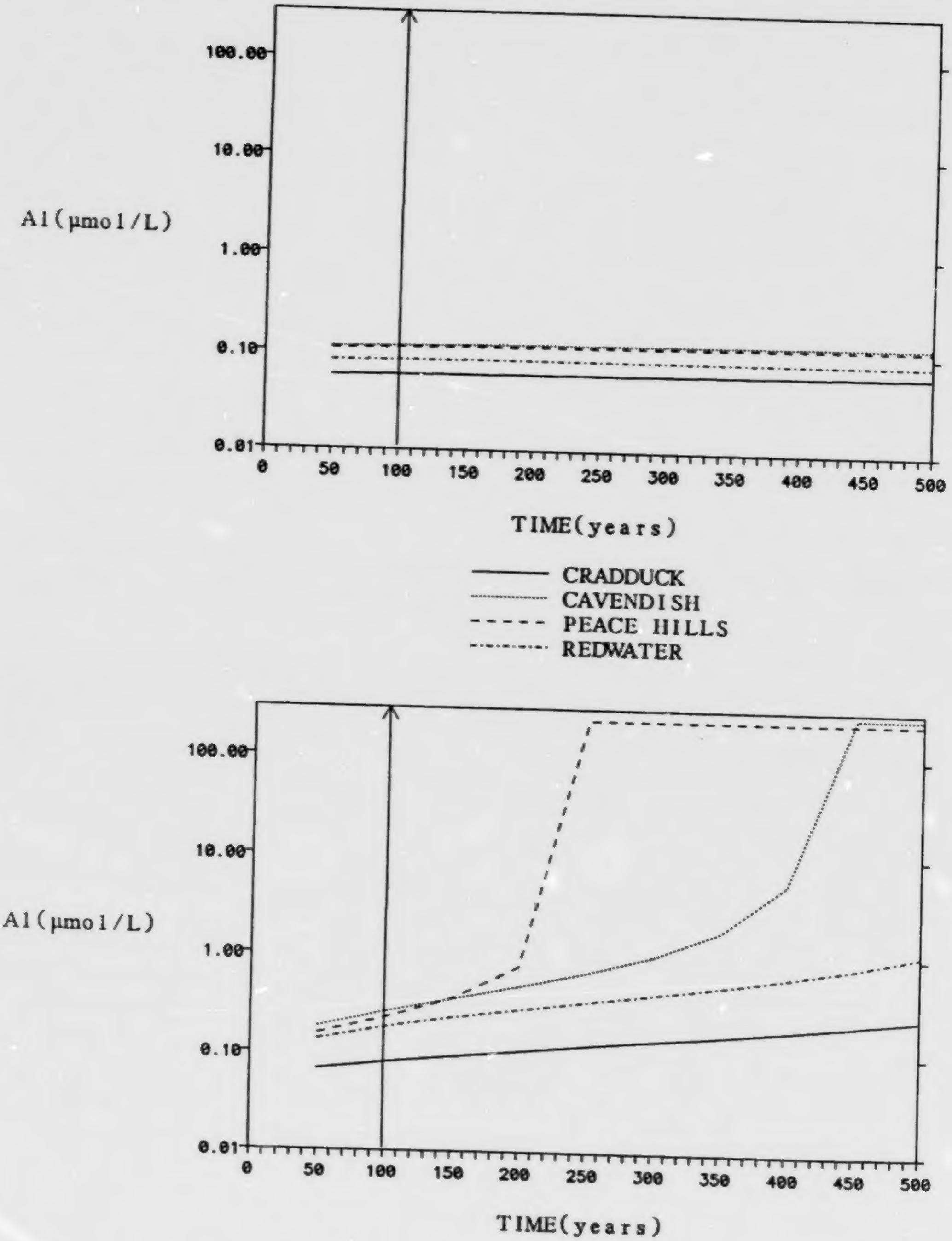


Figure 10. Model predictions for change in solution Al concentration in four Chernozemic soils having acid deposition inputs of approximately 0.1 (top) and 1 (bottom) kmol(H^+) ha^{-1} y^{-1}.

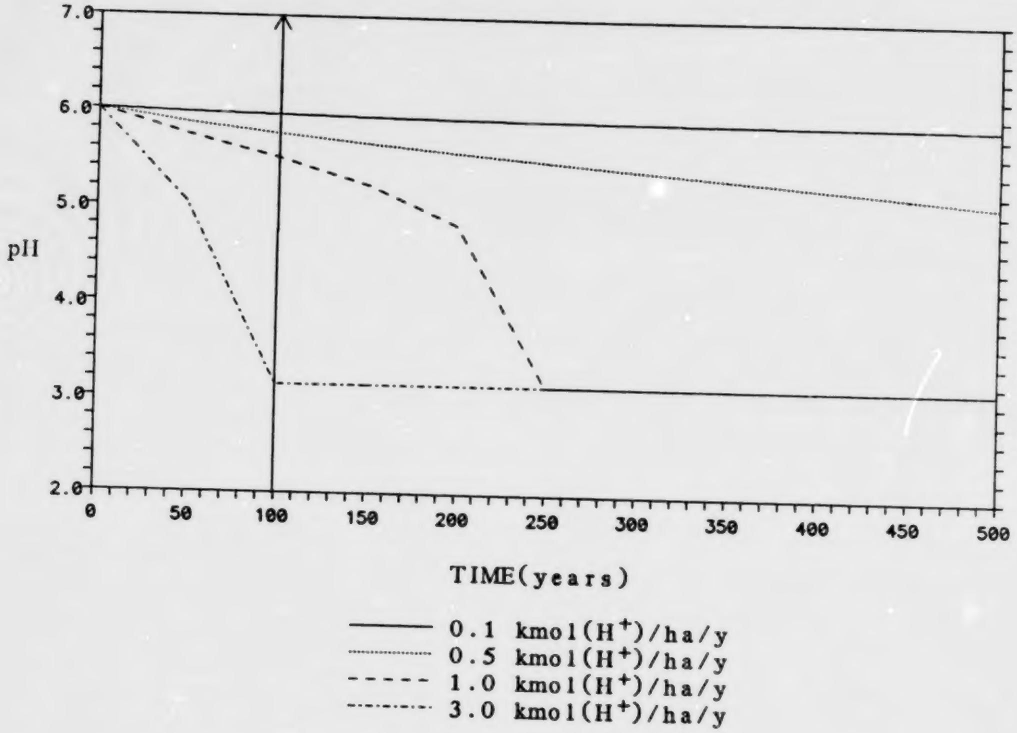


Figure 11. Model predictions for pH change in the Peace Hills series by acid deposition inputs of approximately 0.1, 0.5, 1, and 3 kmol(H^+) ha^{-1} y^{-1} (corresponding to dryfall:wetfall ratios of 1, 10, 20, and 60, respectively).

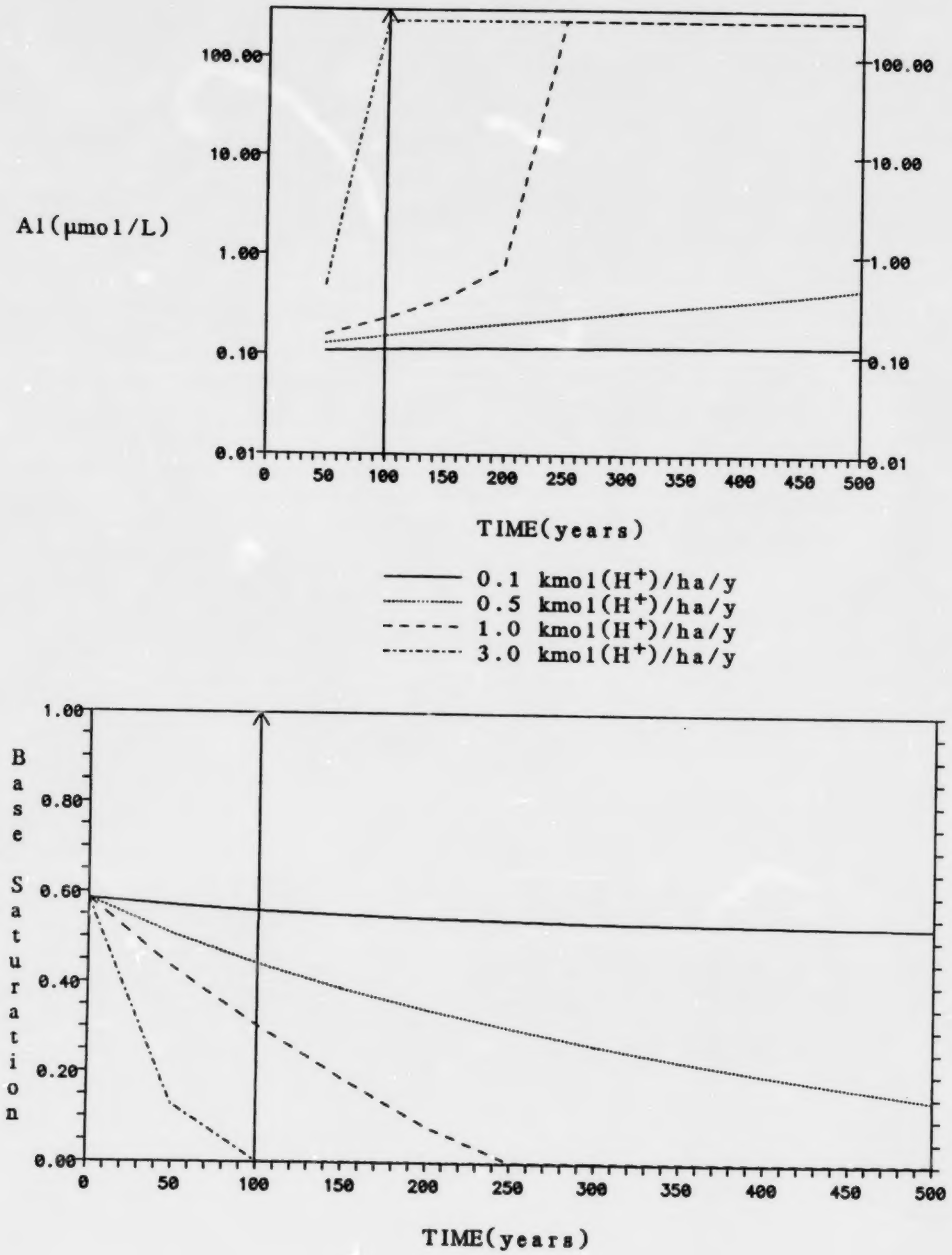


Figure 12. Model predictions for change in solution Al concentration (top) and base saturation (bottom) in the Peace Hills series by acid deposition inputs of approximately 0.1, 0.5, 1, and 3 kmol(H^+) ha^{-1} y^{-1} (corresponding to dryfall:wetfall ratios of 1, 10, 20, and 60, respectively).

Precautionary statements about use of the model on agricultural soils were made in earlier sections. In particular, it was not intended to simulate acid input by fertilizers, steady state conditions are assumed, and results for soils with pH($CaCl_2$) somewhat greater than 5.0 are questionable. The simulation, nevertheless, shows large differences in soil response with different acid inputs. This exercise primarily demonstrates the usefulness of the modelling approach for comparing different soils, for predictive ability and quantifying responses.

5.4.3 Discussion

Application of the Bloom and Grigal (1985) model to a few Chernozemic soils indicated that response to addition of about 0.1 kmol (H^+)ha^{-1} y^{-1} (1.6 kg S ha^{-1} y^{-1}) would be slight. Severe effects such as decline in pH and base saturation to the point of inducing Al toxicity would occur after about 200 years. A loading of 3 kmol(H^+)ha^{-1} y^{-1} (48 kg S ha^{-1} y^{-1}) would have drastic effects within 50 years in some soils. Sandy soils of low CEC are most susceptible. Adverse effects will occur soonest in those soils which already have relatively low pH and base saturation levels.

The model predictions are extreme; that is, the calculated soil responses are worse than can reasonably be expected because of the various assumptions made. Two of the assumptions are that exchange of H^+ for base cations is complete and that no counteracting forces are present. Some counteracting forces include neutralization by basic substances in the polluting medium itself (i.e., in acid rain), nutrient recycling, mineral soil decomposition or weathering, and cation exchange.

Nutrient cycling is an important consideration in acidification impact studies. Bases are taken up by plants and returned to the soil by decomposing roots and aboveground remains. Nutrients leach out of living plant tissue in forest canopies, and similar processes may occur in grasses and crops as well. However, plant growth also generates acidity by exchange of H^+ for base nutrients on root surfaces. The production of CO_2 by soil organisms likewise generates acidity so that the countering effect of nutrient recycling becomes diminished or is exceeded.

Weathering probably contributes significantly to base cation content of soils, but it is difficult to quantify. There does not appear to be any data for soils in southeastern Alberta.

The total content of bases in the exchange complex determines the amount of acidity that can be neutralized. The kinds of cations are important as well, because selectivity for different species varies. The equilibrium of cations on the exchange complex with cations in solution is described by the Gaines-Thomas, Vanselow and/or Gapon equations and selectivity coefficients (Reuss 1983). Equilibrium requirements mean that all acid ions do not replace basic ions and, therefore, the acidification of soil is slower than estimated using the simplifying assumptions. Selectivity coefficients are necessary data for more detailed modelling of acid deposition effects.

The extent of movement of desorbed cations out of the 25 cm layer depends on the quantity of water that flows through. In modelling the effects of acid deposition on leaching, Reuss (1980), Arp (1983), Bloom and Grigal (1985), and others use a "precipitation minus evapotranspiration" calculation to estimate leachate quantity: If evapotranspiration is in excess, there is no removal from the system. In the area of the soil under consideration, the actual evapotranspiration is about 30 or 40 cm while the average water surplus is 0-10 cm (Government and University of Alberta 1969). The potential evapotranspiration generally exceeds the actual evapotranspiration. The surplus, therefore, probably results from downward movement of excess soil moisture resulting from input during storm events and during spring thaw. The amount of mobilized cations and accompanying anions leached out of the top 25 cm layer into the layer below will depend on the actual amount and time of contact of soil water with solid surfaces (Bache 1980b). In sandy soils, the extent of contact may be high as compared with finer soils, but the throughflow may be rapid. The movement of leachate is thus difficult to quantify and research in this area is required.

Although drastic effects of acidification would not occur for several decades or even hundreds of years, more subtle changes would occur in soil properties as pH and base saturation slowly decline. A decreased rate of organic matter turnover would result in increased soil organic matter levels. The input of essential nutrients to plants and microorganisms (N and S) could enhance decomposition and the net effect of acid deposition, therefore, is difficult to predict and requires further study. Strong acidification of hayfields, pastures and rangeland by either acid deposition or fertilization could result in development of a turfy surface layer which would eventually affect production (Section 3.1).

Soil structure may possibly be affected by acid deposition in the long term. As base cation levels in the soil diminish, disruption of cation bridge linkages in organo-mineral particles, which are especially important in Chernozemic soils, may result. The building blocks of soil structure can thus be destroyed, but this effect, along with other deleterious effects of acidification, can be reversed by liming.

Plant availability of nutrients may also be affected by acidification. While some micronutrients (namely Fe, Mn, Zn, Cu, and Ca) become increasingly available with increasing acidity, the major nutrients and other micronutrients become less available.

An effect of acidification of calcareous soils is that sorbed P may become solubilized. The acid neutralizing capacity of lime in soils can be very high. The time to completely neutralize lime can be calculated assuming either partial or complete reaction. Calcareous Chernozemic soils occur extensively in some areas. For example, fine-loamy Calcareous Black Chernozemic soils on glacial till occur in the Dogpound Benchland physiographic district north of Calgary (Crossfield area). Preliminary examination of soils conducted in this area for the ADRP indicate that the $CaCO_3$ equivalent percentage in the topsoil is about 1%. Assuming a bulk density of 1.3 Mg m^{-3} in a 25 cm tilled layer, one ha to a depth of 25 cm would weigh 3250 tonnes. The $CaCO_3$ content then is 32.5 tonnes or about 325 kmol. One kmol $CaCO_3$ neutralizes 2 kmol H^+. Therefore, it would require about 6500 years to neutralize the $CaCO_3$ at 0.1 kmol(H^+)ha^{-1} y^{-1} input. The pedon of the Calcareous Black Chernozemic described in Table 12 (Section 4.5.8) has about 3% $CaCO_3$ equivalent in its surface horizon and neutralization would require three times as long as in the example above.

Due to the assumption of complete equivalent generation of acidity for each unit of S or N deposition, the above calculations likely represent the minimum number of years for neutralization in each case. Factors which retard neutralization are the same as those discussed previously for simulation results.

An overriding issue in considering the effect of acid deposition on Chernozemic soils is that most of them are under cultivation and are fertilized at varying input levels. The strong acidifying effects of fertilization are well documented. In several reviews of this problem in recent years, it has been concluded that liming will have to become a general practice in order to restore productivity in lands degraded by acidification. Any acidification due to atmospheric deposition will thus be neutralized as well. Where liming practices are, or will be, carried out, soil responses to acid deposition are not likely to be important concerns. However, research and monitoring of effects from high acid loadings near sources need to be continued.

5.5 SOLONETZIC SOIL IMPACTS

5.5.1 Sensitivity Ratings

The area of Solonetzic soils in Alberta is about 42,960 km^2. None of these soils are presently regarded as being highly sensitive to acid deposition effects, but about one-third are considered to be moderately sensitive (Holowaychuk and Fessenden 1986). Those which are relatively sensitive include soils of the Solonetz great group which occur on coarse parent materials or on shallow glacial deposits overlying residual materials. The Gray Solonetz subgroup is also in the moderately sensitive group because it lacks the Chernozemic type A horizon characteristic of prairie Solonetzic soils; it is thus relatively more leached and lower in colloid and base cation content in the A horizon.

5.5.2 Model Predictions

Pedons of two Solonetzic soil series were chosen for application of the model. The Camrose series is a Black Solodized Solonetz developed on fine-loamy morainal deposits (Table 17, Section 4.6.7). The Brownfield series is a Dark Brown Solod also developed on fine-loamy glacial till (Table 19, Section 4.6.7). The two soils are compared with each other at similar acid loading levels in Figures 13 to 15.

Both these soils have pH($CaCl_2$) values which, at 4.8 and 4.9, are already quite low. Further change in pH as well as in base saturation is minor at the lowest acid input level (approximately 0.1 kmol(H^+)ha^{-1} y^{-1} input, or D:W=1). Al content, initially at about the 1.0 µM level, likewise changes only slightly. The pH in both soils drops steadily at the higher acid input level (approximately 1 kmol(H^+) ha^{-1} y^{-1} input or D:W=20). The pH drop in 100 years is approximately 0.2 units for the Camrose soil and about 0.4 units for the Brownfield soil. The base saturation likewise drops more rapidly in the Brownfield soil. The different responses are likely due to lower CEC and exchangeable base content in the Brownfield soil. The Al content in both soils increases with time, but does not reach the toxic level of 10 µM for 250 years in the case of the Brownfield soil, and 350 years in the case of the Camrose soil.

5.5.3 Discussion

Although a coarse textured Solonetzic soil was not selected for this modelling exercise, it can be assumed that responses in such soils would occur at higher rates than in fine textured soils as was observed with Chernozemic soils in the previous

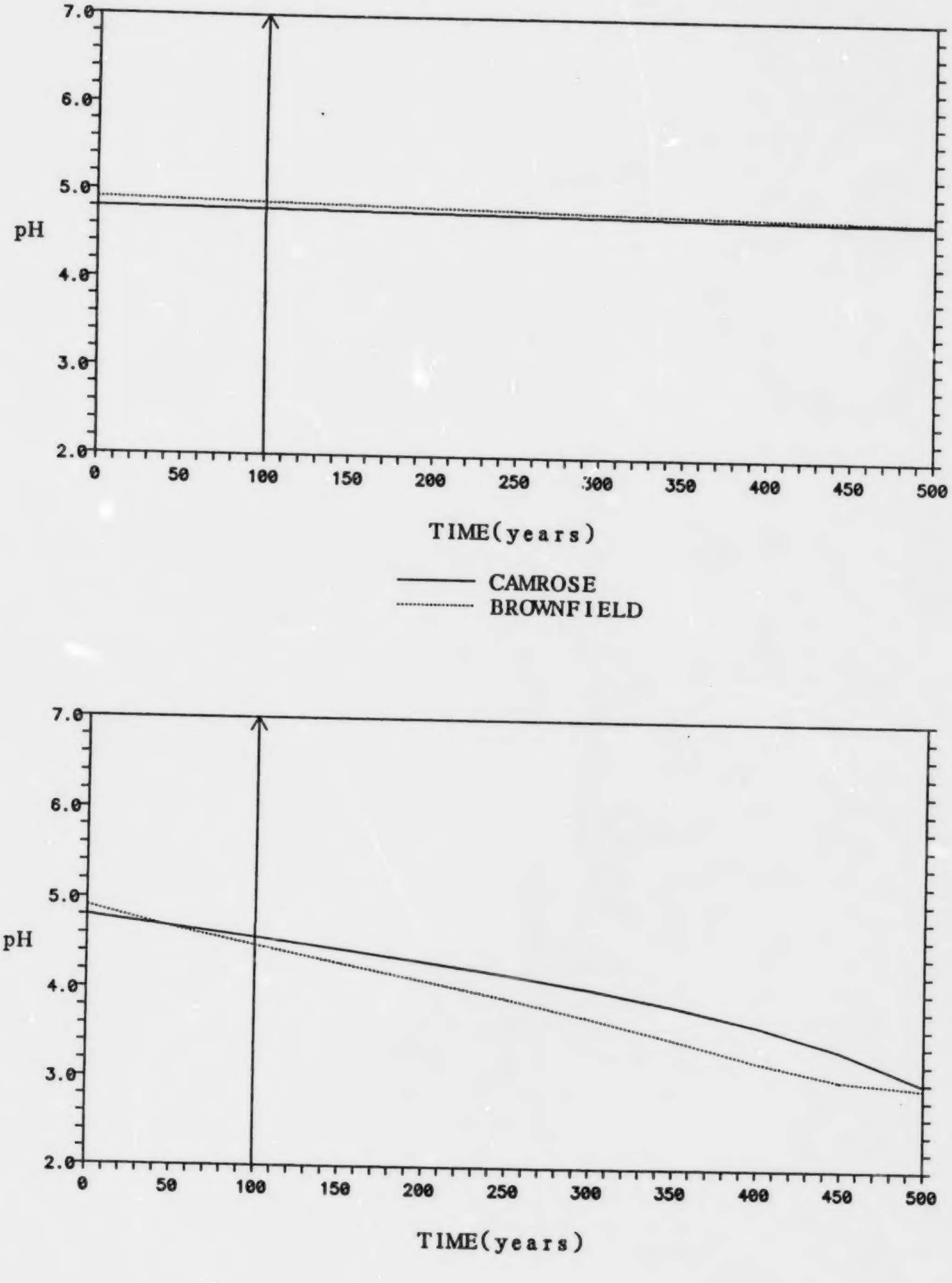
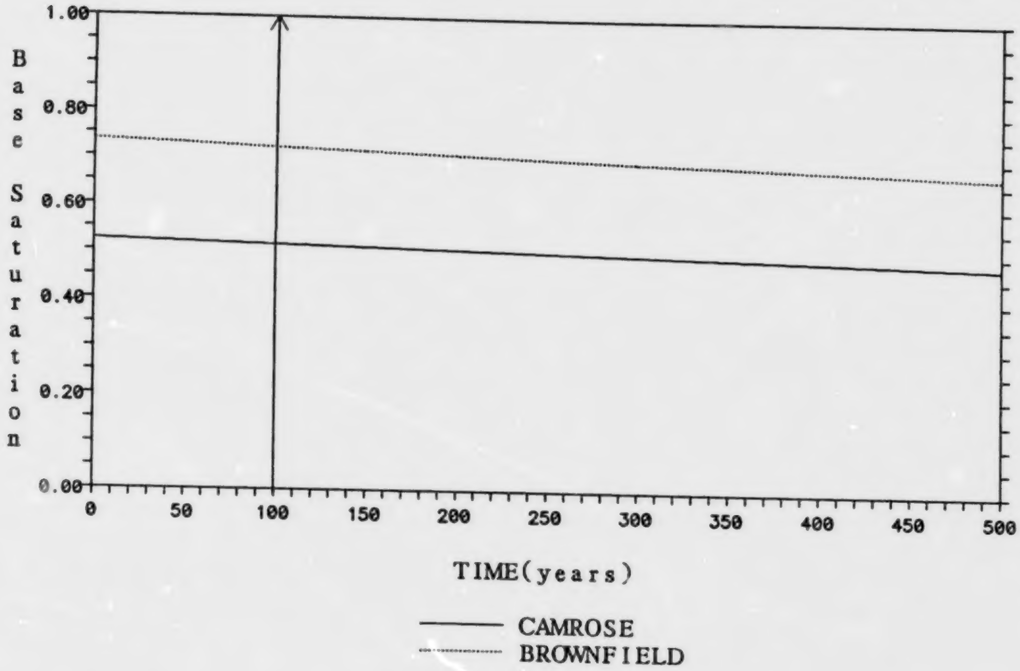


Figure 13. Model predictions for pH change in two Solonetzic soils having acid deposition inputs of approximately 0.1 (top) and 1 (bottom) kmol(H^+) ha^{-1} y^{-1}.



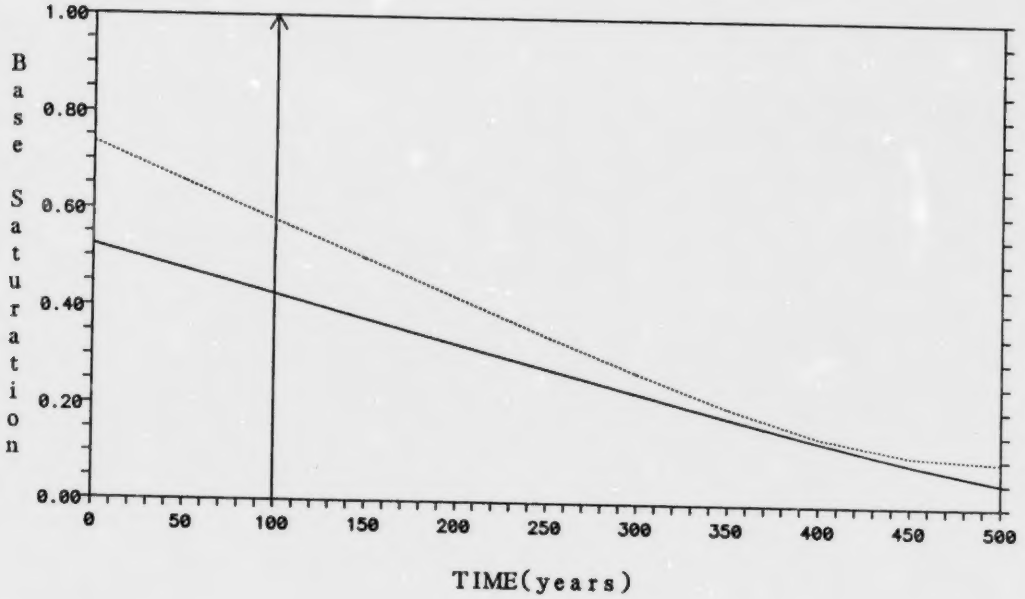


Figure 14. Model predictions for change in base saturation in two Solonetzic soils having acid deposition inputs of approximately 0.1 (top) and 1 (bottom) kmol(H^+) ha^{-1} y^{-1}.

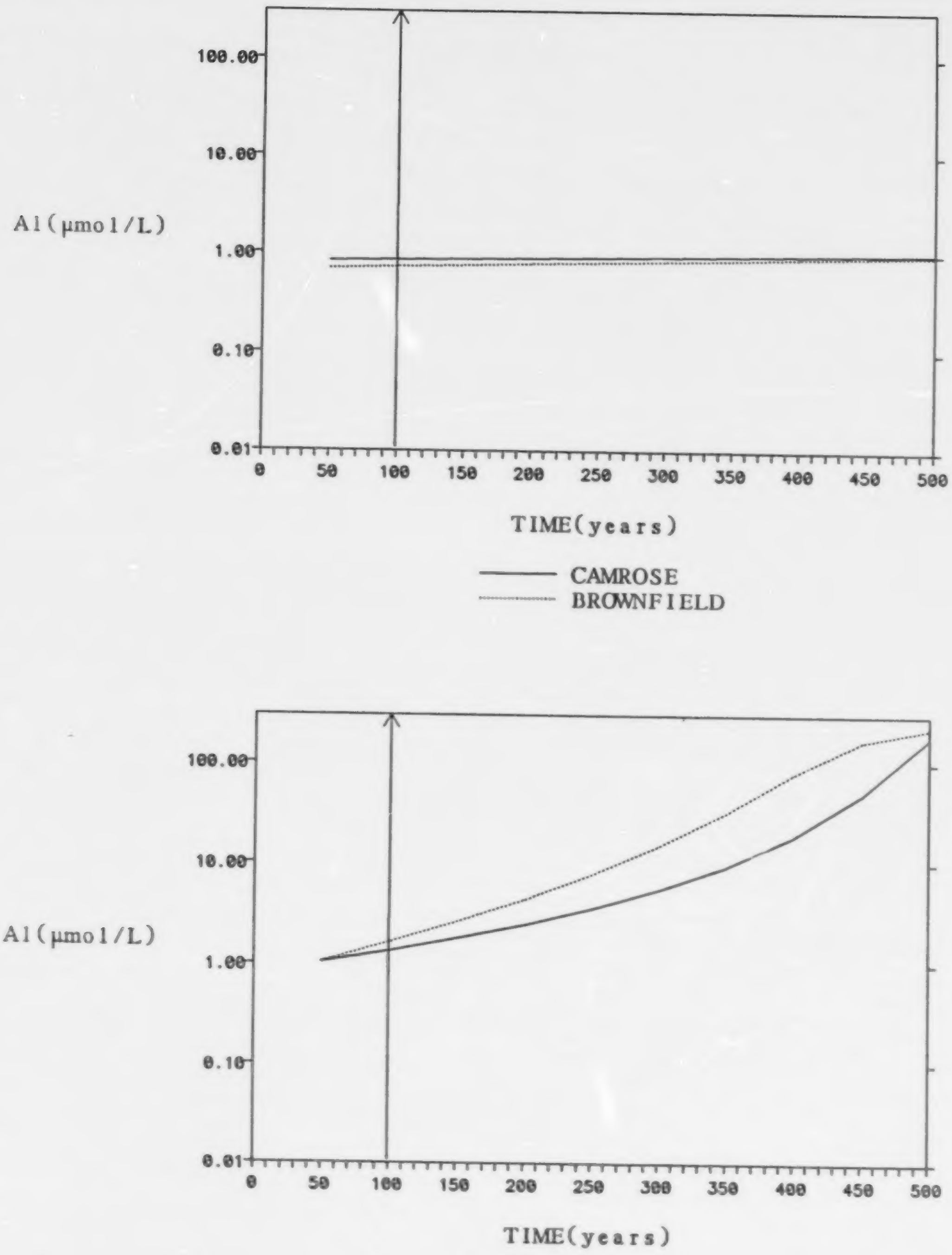


Figure 15. Model predictions for change in solution Al concentration in two Solonetzic soils having acid deposition inputs of approximately 0.1 (top) and 1 (bottom) kmol(H^+) ha^{-1} y^{-1}.

section. Problems of Al toxicity may be expected to occur in such soils in somewhat less than 100 years.

For Solonetzic soils in the grassland zone, the general discussion and conclusions regarding response to acid inputs are similar to those for Chernozemic soils (Section 5.4.3). The susceptibility of these soils to change in pH and in other properties has been demonstrated in parts of Alberta (Section 3.10). The concerns with fertilization and probable adoption of liming practices will override concerns regarding acidification from atmospheric deposition. Many areas of Solonetzic soils are used for rangeland and, therefore, are not as intensively managed as cultivated soils. Very low levels of acid deposition should not markedly change these soils as demonstrated by application of the model. Periodic evaluation of both cultivated and non-cultivated soils in the vicinity of emitters of acid producing substances should be carried out, however, to determine if ameliorative practices are necessary from time to time. The negative acid deposition effects, the possible nutritional benefit of these inputs to agricultural production, and the management measures required to cope with acidification effects need to be quantified to enable determination of any compensation to land owners.

Gray Solonetzic soils are likely more similar in their general properties and nutrient dynamics to Luvisolic soils than to grassland Solonetzic soils. Comments regarding Luvisolic soils in the following section will, therefore, be generally applicable to the Gray Solonetz and Gray Solod subgroups of the Boreal regions.

5.6 LUVISOLIC SOIL IMPACTS

5.6.1 Sensitivity Ratings

The area of Luvisolic soils in Alberta is approximately 203,000 km^2. Most of these soils are regarded as being moderately sensitive to acid deposition; less than 5% are considered to be highly sensitive. The highly sensitive group consists predominantly of Orthic Gray and Brunisolic Gray Luvisols developed on sandy and coarse-loamy parent materials of glaciofluvial and eolian origin. They often occur in association with sandy Brunisolic soils.

Most Luvisolic soils are moderately sensitive to acidification as a consequence of relatively low base status in the A horizons. These horizons have been depleted of colloids which account for most of the soil exchange capacity. The exchange capacity of surface litter layers can be high on a unit weight basis, but the contribution to total exchangeable bases and exchange capacity on a unit area or volume basis is low because of very low bulk density. Furthermore, Luvisolic soils form under forest vegetation which does not recycle base nutrients as efficiently as grassland systems. Surface horizons of Luvisolic soils may thus be low in base saturation as well as total exchange capacity.

5.6.2 Model Predictions

Five soils were selected for simulations of response to acidic inputs according to the model of Bloom and Grigal (1985). The Culp and Leith series are coarse textured members of the Orthic Gray Luvisol and Dark Gray Luvisol subgroups, respectively. The Breton series is an Orthic Gray Luvisol developed on fine-loamy glacial till. The

Nosehill and Tom Hill series are both developed on fine-loamy till and both occur in the Edson area. The Tom Hill is an Orthic Gray Luvisol while the Nosehill is a Podzolic Gray Luvisol. Descriptions for these soils are given in Tables 22 to 26, Section 4.7.6.

The pH response to the lowest acid input level (0.1 $\mathrm{kmol(H^+)ha^{-1}\ y^{-1}}$) is as weak as it was with Chernozemic and Solonetzic soils (Figure 16). The pH drops at a higher rate at the higher acid input level (Figure 16). The Culp soil has the highest rate of pH drop; in 100 years it drops from pH 5.8 to about 4.9. The Leith drops in 100 years from approximately pH 5.9 to 5.6; the Breton from pH 5.6 to 5.3; the Tom Hill from pH 5.4 to 4.7; and the Nosehill from pH 4.4 to 4.0.

There is a small drop in base saturation in all soils at the lowest acid input rate (Figure 17). The Culp drops most rapidly in base saturation at the higher acid input level, as did its pH. The drop is from 87% to about 44% in 100 years. The rate of decrease is lowest in the Leith series which changes from 89% to about 70% in 100 years. The Leith series is characterized by a higher CEC and exchangeable base content which is due to its higher clay and organic matter content as compared to the Culp series. The rates of decrease in the other series are intermediate to the Culp and Leith. The Nosehill series initially has a relatively low base saturation (61%) and drops to about 35% in 100 years. All soils eventually lose almost all their base cations.

The Al contents rise slightly over time at the low acid input rate (Figure 18). The highly acidic Nosehill series has a relatively high Al content (about 3 µM) to begin with. Actual measurements of Al content in this and other similarly acidic soils should be carried out since some species may be sensitive to these levels. The other soils do not reach the Nosehill starting levels within 100 years even at the higher acid input levels. The Nosehill Al level increases to about 9 µM in 100 years at the higher input level. All series eventually increase to toxic Al levels; the order from soonest to latest is Nosehill, Culp, Tom Hill, Breton, and Leith.

5.6.3 Discussion

The responses of Luvisolic soils to acidic inputs are generally similar to those of Chernozemic and Solonetzic soils. The response rates are highest in coarse-textured soils with low CEC and exchangeable base content. The pH and base saturation in Luvisolic soils are relatively low, however. Therefore, critical levels of pH and Al content may be reached within a shorter period of acid deposition than they would be in other soils. In addition to Al mobilization, the release of other toxic elements to soil solution is also a concern. It has been argued that strongly acidic Luvisolic soils, as well as soils of other orders, cannot be rated as being highly sensitive to acid deposition because the acid inputs cannot make them much more acidic than they already are. The model calculations, however, indicate that relatively high Al levels can be attained in a relatively short period. A higher sensitivity in terms of Al response may be important to indicate in soil sensitivity rating procedures. Further research in the ion exchange and aluminum chemistry of highly acidic soils seems necessary.

The pedon of the Nosehill series described in Table 26, Section 4.7.6 has a 5 cm thick Bf horizon which contains 1.55% oxalate extractable Fe and Al. The Fe and Al

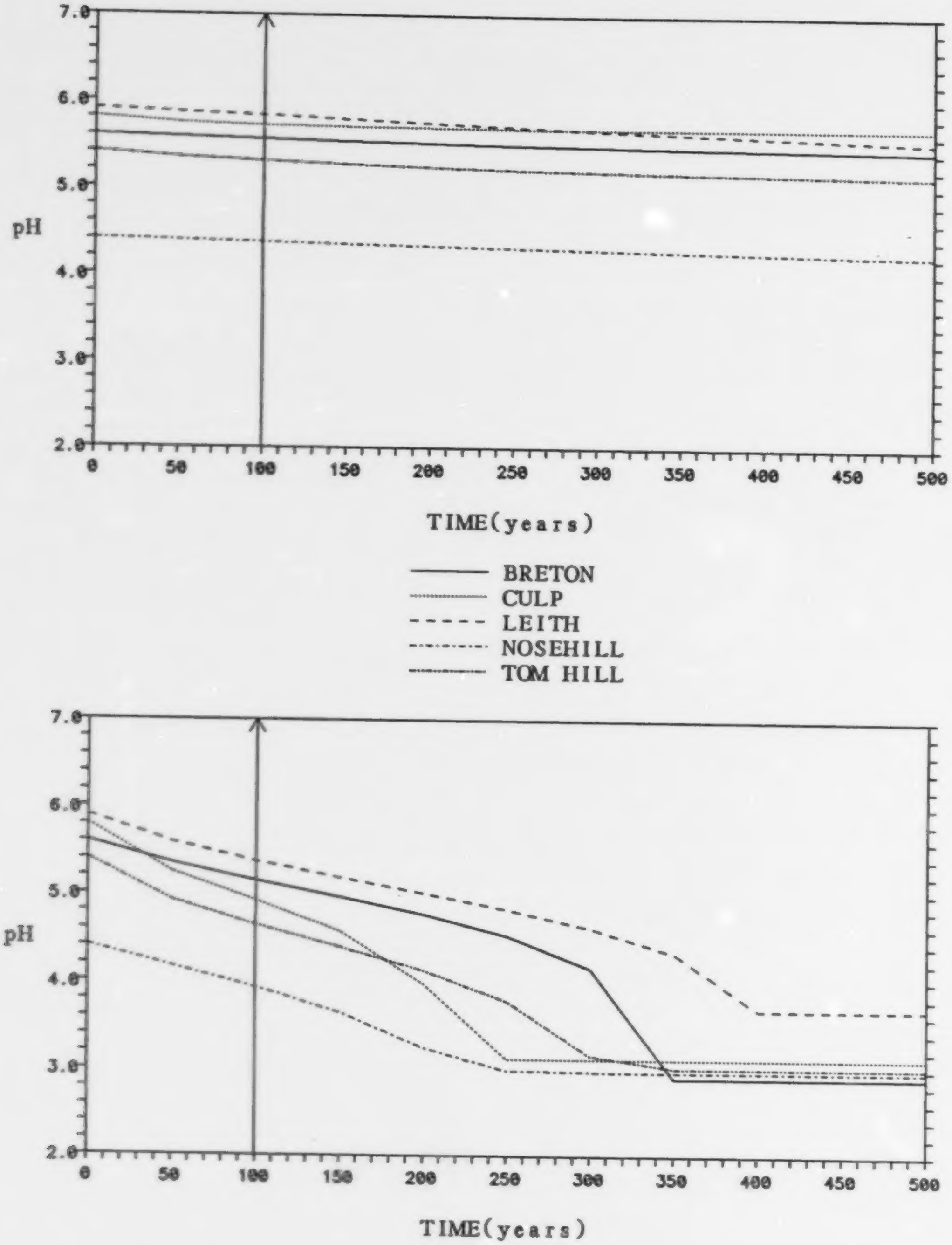


Figure 16. Model predictions for pH change in five Luvisolic soils having acid deposition inputs of approximately 0.1 (top) and 1 (bottom) kmol(H^+) ha^{-1} y^{-1}.

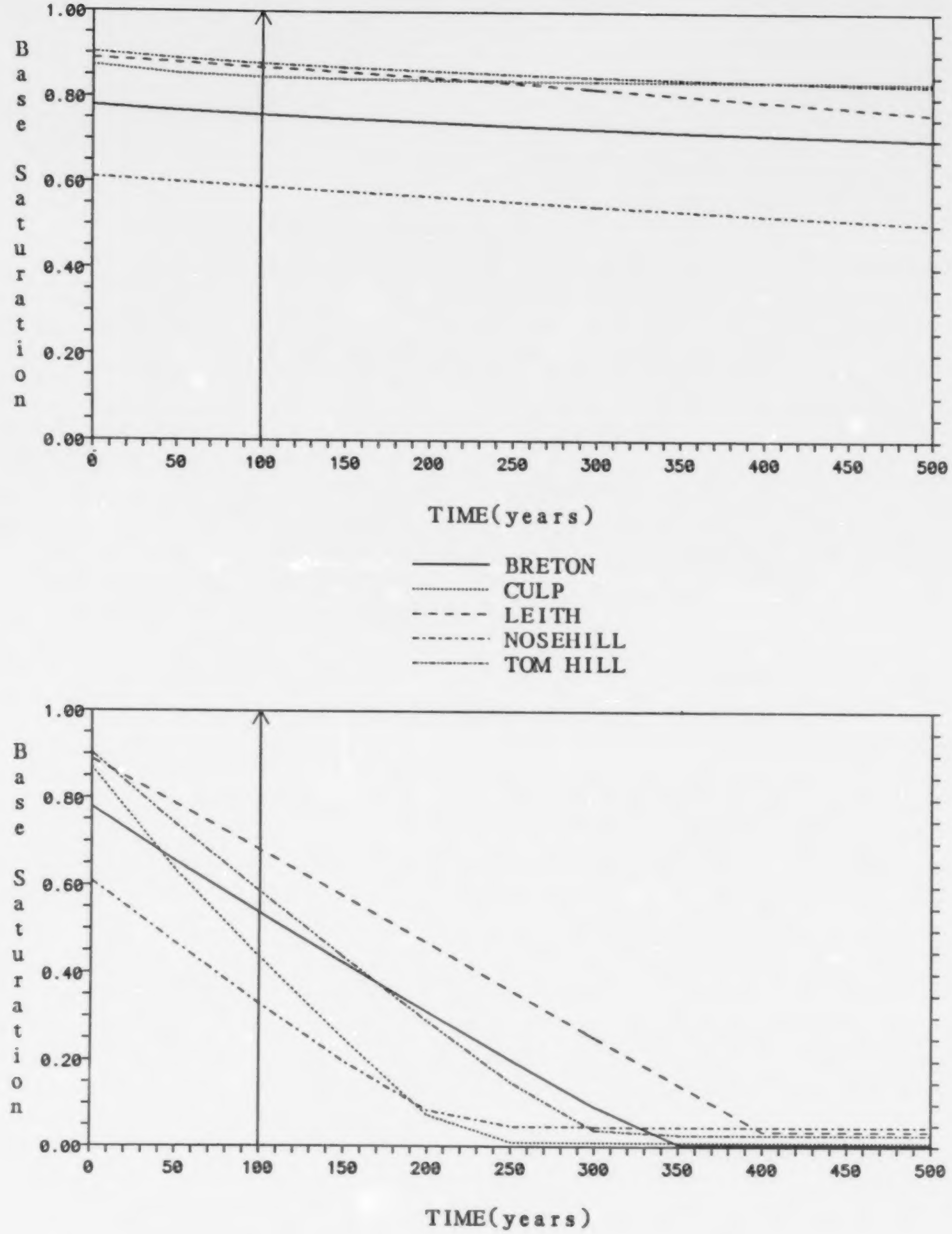


Figure 17. Model predictions for change in base saturation in five Luvisolic soils having acid deposition inputs of approximately 0.1 (top) and 1 (bottom) kmol(H^+) ha^{-1} y^{-1}.

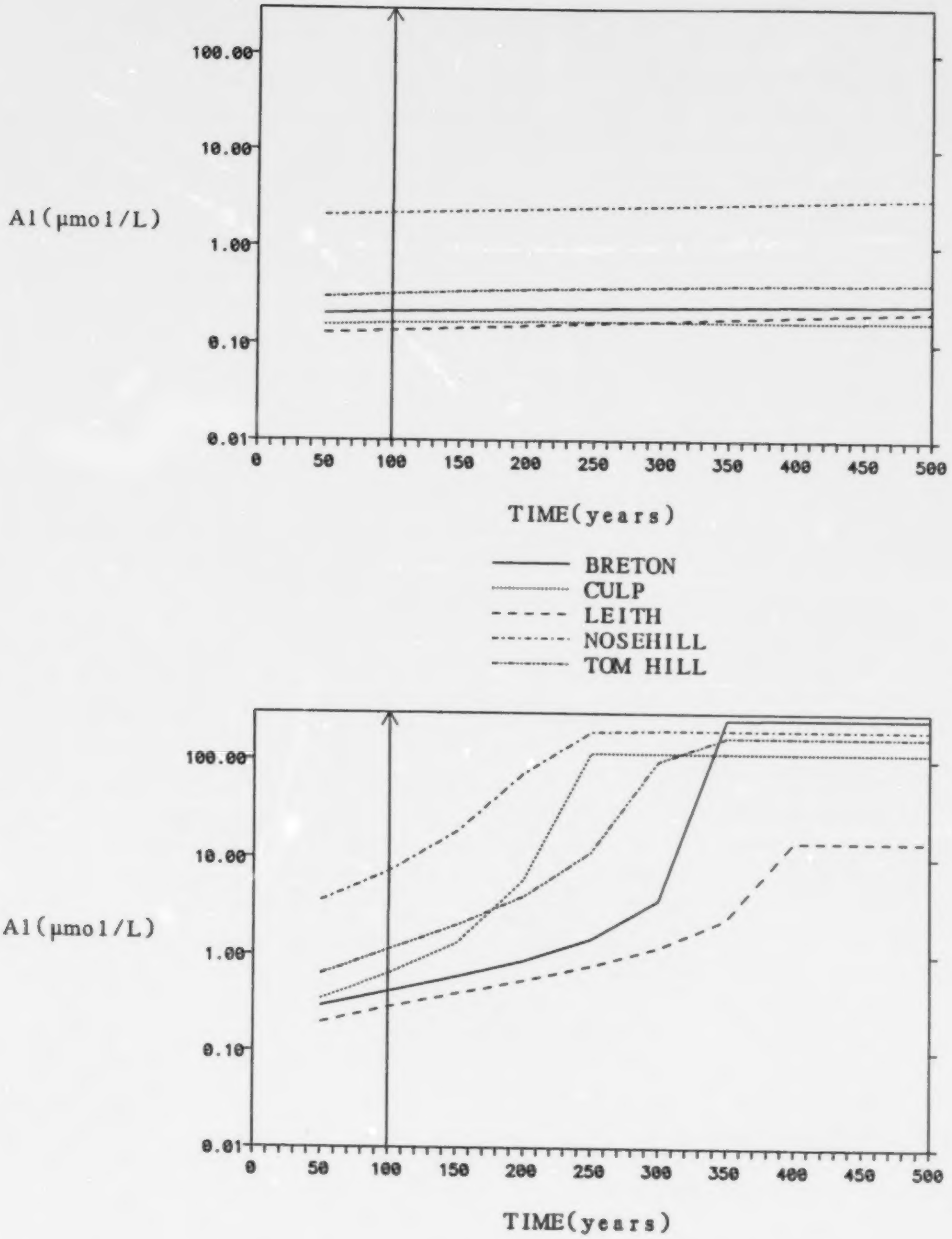


Figure 18. Model predictions for change in solution Al concentration in five Luvisolic soils having acid deposition inputs of approximately 0.1 (top) and 1 (bottom) kmol(H^+) ha^{-1} y^{-1}.

are in hydrous oxide forms which are capable of adsorbing significant quantities of sulphates. The effect of SO_4^{2-} sorption would be to retard leaching of bases from the soil and to significantly increase the time over which acidification and base loss would occur. However, there are no data on the sulphate sorbing capacities of these soils and the influence of Al and Fe hydrous oxide on soil acid deposition effects cannot be predicted.

As discussed in previous sections, the calculated responses of Luvisolic soils are exaggerated due to the assumptions made. Weathering rates and products, and recycling of base cations and other nutrients need to be considered. Other possible effects of acid deposition in Luvisols include those listed in Table 3, Section 3.11. Reports from other parts of the world suggest that organic matter decomposition decreases due to acid inputs. The consequence in forest soils would be an increase in the total carbon and nutrient pool in the litter layer. A possible positive effect on plant growth due to N and S additions in acid deposition has been suggested. The increase in acidity, however, could reduce the availability of these and other nutrients. Little research on these effects on forest soils has been carried out in Alberta. Studies of some of those impacts would necessarily be of long duration and, therefore, monitoring as well as experimental approaches to research would need to be considered.

5.7 BRUNISOLIC AND PODZOLIC SOIL IMPACTS

5.7.1 Sensitivity Ratings

About 40-45% of the 53,000 km^2 of Brunisolic soils in Alberta are considered to be highly sensitive to acidic deposition (Holowaychuk and Fessenden 1986). These soils are mainly Eluviated Eutric Brunisols and Eluviated Dystric Brunisols developed on sandy glaciofluvial and eolian deposits. Brunisols developed on finer textured materials such as Cordilleran and Continental tills in the foothills region have a low sensitivity rating (Holowaychuk and Fessenden 1986). Podzolic soils do not occur extensively and are mainly found in association with Brunisols in foothills and Alpine regions. Those developed in coarse materials are rated as highly sensitive. A small area of about 390 km^2 of Orthic Humic Podzols and associated Dystric Brunisols occurring west of Grande Cache is rated as highly sensitive (Holowaychuk and Fessenden 1986).

5.7.2 Model Predictions

Two soils were selected for acid response simulations. The Firebag soil is an Eluviated Dystric Brunisol developed on sandy glaciofluvial materials in northeastern Alberta (Table 30, Section 4.8.4). It is characterized by a very low CEC and exchangeable base content. The Robb series is an Eluviated Dystric Brunisol developed on fine-loamy glacial till in the foothills region (Table 31, Section 4.8.4). It has a relatively high CEC but pH and base saturation percentage are very low. The two soils are compared at different input levels in Figures 19 to 21.

The Robb soil shows a weak response in pH, base saturation, and Al at the low acid input level. It is similar in this regard to soils discussed previously. The Firebag soil shows the strongest response of any of the soils at the low input level. Within 100 years, its pH drops from 5.1 to about 4.6, its base saturation drops from 31% to less than 10%, and Al levels rise from about 0.9 to 2μM (Figures 19 to 21).

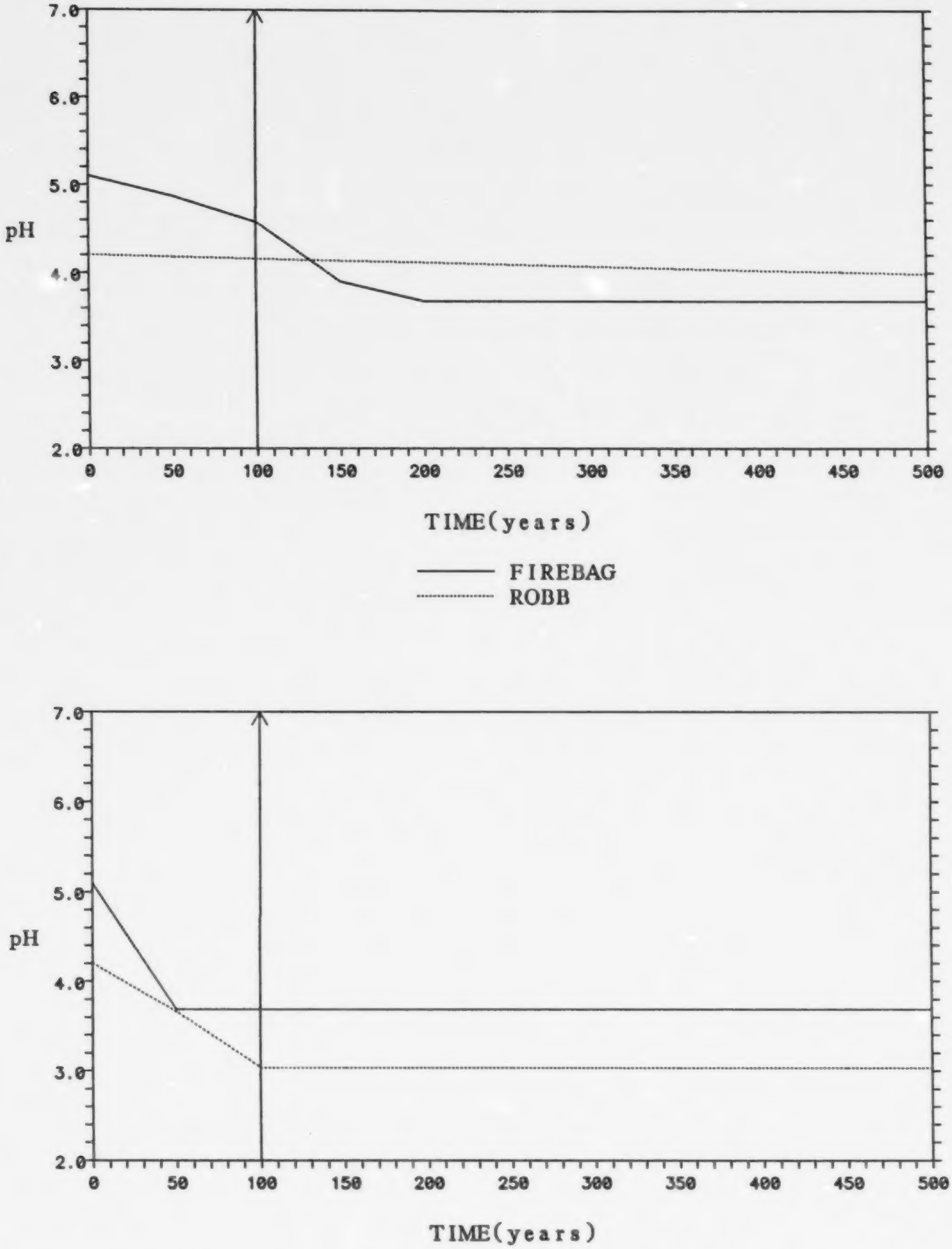


Figure 19. Model predictions for pH change in two Brunisolic soils having acid deposition inputs of approximately 0.1 (top) and 1 (bottom) kmol(H^+) ha^{-1} y^{-1}.

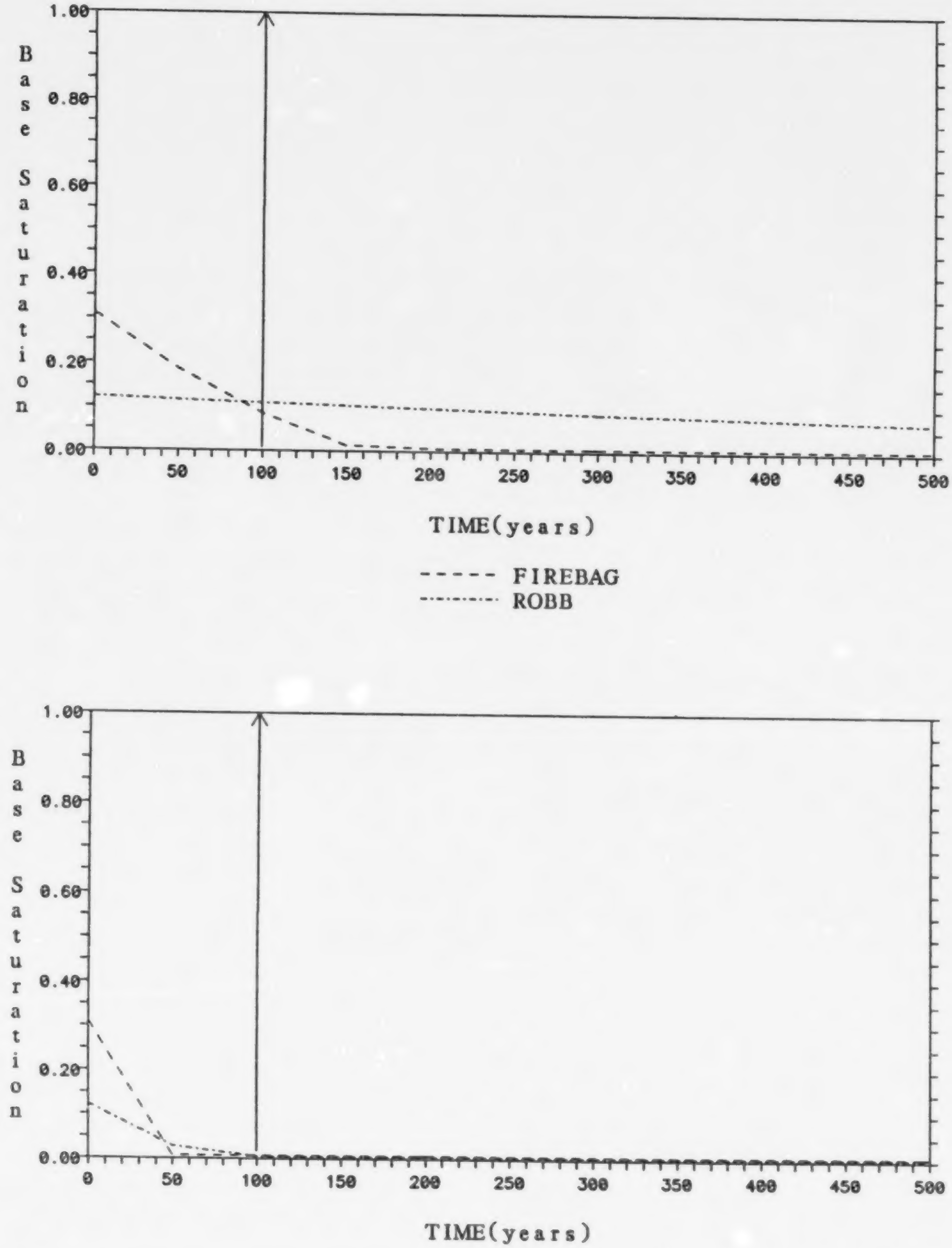


Figure 20. Model predictions for change in base saturation in two Brunisolic soils having acid deposition inputs of approximately 0.1 (top) and 1 (bottom) kmol(H^+) ha^{-1} y^{-1}.

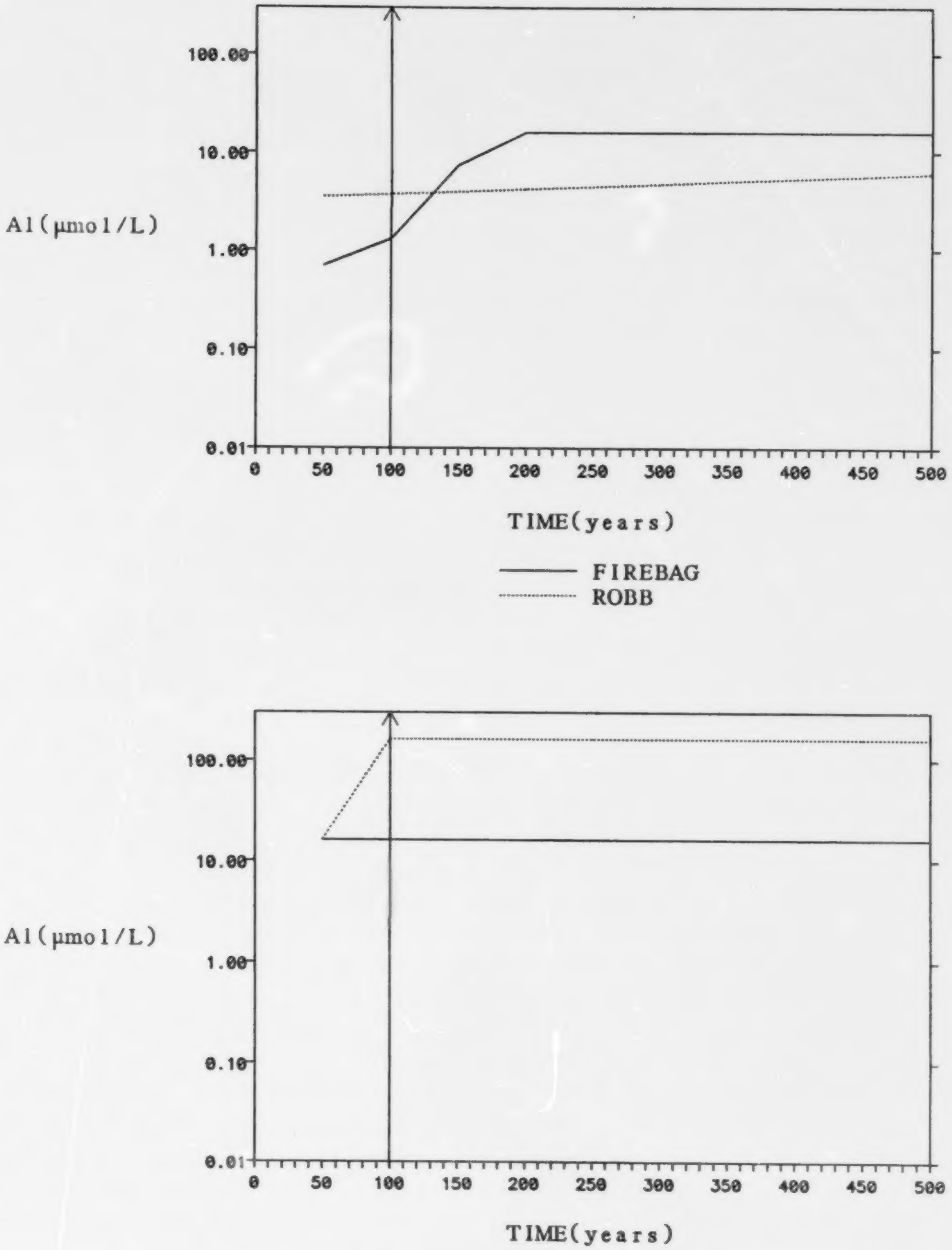


Figure 21. Model predictions for change in solution Al concentration in two Brunisolic soils having acid deposition inputs of approximately 0.1 (top) and 1 (bottom) kmol(H^+) ha^{-1} y^{-1}.

The responses at the higher acid input level are drastic in both soils (Figures 19 to 21). The pH of the Firebag soil drops rapidly within 50 years from 5.1 to 3.7. The Robb pH drops from 4.2 to 3.7 in 50 years, and to about 3.0 in 100 years. Both these soils have initially low base saturation percentages and these diminish to almost zero in 50 years. The calculated Al content at 50 years is alarming since it is above 100 µM for both soils. The Al content at time zero is unknown for these soils, but it is likely below 10 µM for the Firebag soil and 10 µM or higher for the highly acidic Robb soil. As with the Nosehill Luvisolic soil discussed previously, the simulation results suggest that the current status of Al in foothill soils should be examined in relation to toxic effects on vegetation.

5.7.3 Discussion

The acid deposition response simulations indicate that sandy Brunisolic soils are among the most sensitive in the province and that particular attention should be given to these soils and the ecosystems they are components of. Finer-textured Brunisols are considered to be less sensitive, but the simulations indicate there could be problems related to high Al in soils of very low pH. Very high Al levels were predicted for the Firebag soil. It is unlikely, however, that such high levels could develop because these soils are so sandy and devoid of easily weatherable minerals that the total Al in the system may not be sufficient to contribute to high soluble Al levels.

Comments regarding exaggerated responses due to the model assumptions apply to Brunisolic soils as they did to soils discussed previously. Replenishment of bases due to weathering is not likely to be substantial in sandy soils due to lack of weatherable minerals as noted above. Quartz is predominant in the sand and silt fractions; feldspars are also likely present and may contribute some bases upon breakdown. As in other parts of the province, there is some input of bases in precipitation which would counteract acidification and base loss. The levels are low, however, and the overall low base status of the soil suggests that the system is very delicate and that the nutrient budget of the vegetation is highly important. Foster and Morrison (1976) have suggested that jack pine stands on similar soils in Northern Ontario maintain soil reserves of plant-available or mineralizable nutrients by replenishment from precipitation and vegetation-soil nutrient cycling.

Nutrient uptake by jack pine communities in northeastern Alberta can be very low. Estimates of uptake in a jack pine-lichen stand are as follows (in kg ha^{-1} y^{-1}): N=5, P=0.4, Ca=6, Mg=2, and K=2 (McGill et al. 1980). In a stand of jack pine mixed with aspen, white birch and other species, nutrient uptake estimates were as follows: (in kg ha^{-1} y^{-1}) N=22, P=2, Ca=19, Mg=6, and K=8. These latter levels approach those reported by Foster and Morrison (1976) in Northern Ontario for similar stands. The levels of uptake in the first stand above are very low by comparison. On an molar basis, the uptake of all bases is only about 0.5 kmol(+)ha^{-1} y^{-1}. Most of these are recycled through the system. The amount contributed by weathering is unknown. At these low fluxes of bases in these ecosystems, it can be seen that acidic inputs of moderate to high levels are likely to seriously disturb nutrient balance.

Relatively low soil pH and altered nutrient status of pine trees in the vicinity of SO_2-emitting natural gas processing plants near Whitecourt, Alberta, have been reported (Legge 1980). Significantly thicker LFH layers on Brunisols near the gas plants as compared with LFH thicknesses in similar soils a few kilometres away were noted by two of the authors (Abboud and Turchenek) during a field trip to the area. These observations indicate that soil responses predicted or observed elsewhere may indeed be occurring in some locations in Alberta. Thorough investigation of these responses is required for determining cause-effect relationships and for enabling extrapolation and prediction of impacts.

5.8 ORGANIC AND ORGANIC CRYOSOLIC SOILS

5.8.1 Sensitivity Ratings

Practically all of the approximately 104,500 km^2 of Organic soils in Alberta are considered to be highly sensitive to acid deposition. The 43,800 km^2 of Organic Cryosols have a low sensitivity rating (Holowaychuk and Fessenden 1986). Organic soils throughout the province are generally in the very strong to medium acid reaction range. Their base status when considered on a volume basis is low, and their base saturation percentage is also relatively low. Further base depletion due to acid inputs would also reduce pH and base saturation levels. Most Organic Cryosols are dominantly extremely to strongly acid in reaction. It is generally considered that acidic inputs will not further acidify these soils or alter their base status significantly.

5.8.2 Discussion

A soil response simulation using the Bloom and Grigal (1985) model was not carried out for any Organic soils. One reason for this is that the model was developed for mineral soils. Model input parameters such as pH-base saturation relationships, Al activity coefficients, and others are different for organic soils than for mineral soils and little information is available regarding these properties. Moreover, Organic soils are generally saturated to the surface or to near the surface. Exchange reactions and base removal from organic soil systems could be very different than those in mineral soils. The model used for mineral soils is, therefore, probably not applicable; development of a model specifically for Organic soils is necessary.

A number of possible effects of acid deposition on peatlands and the factors affecting these, have been reviewed by Gorham et al. (1984). They indicated that the hydrogen ion balance in peat will be determined predominantly by alkalinity or buffering due to cation exchange reactions with surface peat, redox processes at and below the water table, and interaction with water soluble organic matter composed mainly of fulvic and uronic acids. Certain peatlands may be highly vulnerable to rapid acidification because they have little bicarbonate buffering. The most susceptible types of peatland are those with very low alkalinities, a pH of approximately 6.0 in their surface waters, and no inputs of mineral material. The water in these kinds of peatlands is supplied by groundwater and overland flow, but the base cation and bicarbonate supply is very limited. Thus, even small amounts of strong acid inputs are likely to cause major changes in pH and other chemical properties with possible adverse effects on the biotic components of peatland systems (Gorham et al. 1984). Although there are no estimates of the extent of these kinds of peatlands in Alberta, the area could be substantial. Some have been described in central and northeastern Alberta by Turchenek and Lindsay (1982) and Turchenek et al. (1984) .

The acidification of peatlands can have various secondary effects with consequent impacts on biota. Availability of both cationic and anionic nutrients is generally reduced by increased acidity. Heavy metals, some of which may be nutrient elements, can become mobilized with increased acidity. This may affect organisms in the peatland itself. It is also possible that peatland outflow may discharge acid and mobilized toxic metals to the streams and lakes into which they drain, thus affecting chemical properties and biota there. Further effects on nutrient cycling in peatland ecosystems and on biological responses to acidification were discussed in some detail by Gorham et al. (1984). These authors concluded that considerable research into acidification effects on peatland systems is required. In addition to survey, monitoring, and experimental approaches, they suggested that a number of existing lake acidification models be evaluated for application to peatlands.

5.9 GLEYSOLIC SOIL IMPACTS

5.9.1 Sensitivity Ratings

There are about 21,500 km^2 of predominantly Gleysolic soil map units in the acid sensitivity map of Holowaychuk and Fessenden (1986). Most of these are considered to have low sensitivity to acid deposition. One area of about 836 km^2 located northeast of Grande Cache has a high sensitivity rating. Gleysols in this area are developed on loamy skeletal materials and occur in association with Brunisolic Gray Luvisols, Eutric Brunisols, and Organic soils.

5.9.2 Discussion

No acid deposition response simulations were carried out on Gleysolic soils. Gleysols generally are not considered to be sensitive to acid deposition. Such soils receive runoff and subsurface water flowing from other soils in adjacent upland landscape positions and the acid neutralizing capacity is thus increased due to base cations and colloidal materials which are introduced. Moreover, water moves slowly through poorly-drained soils and weathering reactions are likely to be more significant in neutralization of acidic substances than in upland soils.

The impact of acidic substances on Gleysolic soils may be of concern where deposition is high. As with Organic soils, an important consideration is the possibility of introducing acids and mobilized toxic metals to streams and lakes that Gleysolic soil areas drain into. Little is known about these processes and research into acid deposition effects on these soils is needed. Another area of concern is the effect of acidic substances on Gleysols within large wetland complexes including marshes and open water bodies which are valuable as wildlife habitat. Thus there may be unique situations where the effect of acid deposition on Gleysols would require special attention even though the neutralizing capacity of these soils is normally high.

5.10 REGOSOLIC SOIL IMPACTS

There are only about 7400 km^2 of Regosolic soil map units delineated on the map of Holowaychuk and Fessenden (1986). A large proportion of this area is located in the Peace-Athabasca delta. These soils are generally not considered to be sensitive to acid deposition because of continuous replenishment of calcareous mineral sediments by alluvial processes.

Rockland and Rough-Broken lands account for about 35,400 km^2 of Alberta's land area. Two groups of these lands are considered to be sensitive to acidic deposition. One of these consists of granitic rocks in the Precambrian Shield area of northeastern Alberta which occur in association with extremely to very strongly acid Dystric Brunisols on sandy glaciofluvial and morainal materials. The second area of acid sensitive Rockland occurs in Cordilleran areas and consists of practically barren clastic sedimentary rock and rock materials. Coarse-textured Brunisolic and Podzolic soils occur within the Rockland areas. In both cases, the Rockland map areas are designated as being highly sensitive to acid deposition due to the sensitive nature of the coarse textured soils occurring within them.

6. SUMMARY AND CONCLUSIONS

1. The nature of soil acidity was reviewed in terms of defining soil reaction and describing sources of acidity, buffering capacity, and relationships with ion exchange properties, leaching, and weathering. An important consideration is that acidification is a natural process in most soils. Thus, acidification resulting from anthropogenic inputs of acid forming substances is most appropriately viewed in the context of processes which occur during the course of soil formation.
2. Lime potential is a useful concept which reflects the interaction and balance of H^+ and other ions in the soil solution. The composition of leaching solutions should be presented in terms of H_3O^+ and $(Ca, Mg)^{2+}$ rather than pH alone if their reaction with the soil is to be considered. This concept is more suitable than pH alone for use in determining the sensitivity of a soil to acidification and in predicting specific responses to acidification by use of simulation models. Cation exchange capacity, base saturation, pH, and lime potential are interrelated. The degree of base saturation as reflected by the lime potential is a particularly useful relationship in evaluating acid input responses in soils.
3. The effects of acidity and acidification on various soil properties as reported in the literature were reviewed. The predicted effect on organic matter is a reduction in mineralization and, therefore, a buildup of soil organic carbon reserves. This has been observed in some situations but experimental work on this effect is inconclusive.
4. Desorption of base cations from the exchange complex and subsequent loss to subsoil by leaching is one of the main concerns about acid deposition impacts. Loss of cations will result in reduced base saturation, increased acidity, and reduced nutrient status. Leaching losses have been demonstrated in various field and laboratory experiments.
5. Bases removed by leaching will be accompanied by anions such as sulphate or nitrate. However, in sulphate adsorbing soils, loss of bases may be retarded until sulphate saturation occurs.
6. Nutrient availability is influenced by soil reaction. Increased acidity reduces macronutrient and some micronutrient availability. The other micronutrients become mobilized and more readily available with increased acidity.
7. Toxicity by Al and heavy metals brought about by acidification is another major concern. Aluminum may occur in solution at levels toxic to vegetation at pH's below approximately 5.5.
8. The effect of acidification on the major biogeochemical cycles has not been thoroughly investigated. In general, it is predicted that N, S, and P will accumulate in soil with the buildup of organic matter. Nitrification may be the process in the N cycle most susceptible to change in acidity. Phosphorus availability may decrease due to its immobilization in organic matter or on Fe and Al hydrous oxides. However, P in calcareous form may be released upon acidification.

9. Weathering may become accelerated with increased inputs of acidity to soil. The intensity of weathering is dependent on flow pathways of water, residence time of soil solution, composition of the soil, and the degree of acidity. Generally, little information about weathering rates and processes is available, yet it is recognized as a major counteracting force to acidification.
10. In assessing effects of acid deposition, neutralization of acidity by atmospheric base cation deposition, by groundwater discharge, and by erosion must be considered. Neutralization by base cation deposition (in dustfall) is probably a very important process, at least in southern Alberta, yet there is little or no information on the rate or magnitude of this process. Application of calcium carbonate, or liming, for neutralizing acidity is commonly practised in most parts of the world and increased use in Alberta may be desirable.
11. The acidifying influence of nitrogenous fertilizer application is generally many times greater than that resulting from atmospheric deposition of acid forming substances. It has been suggested that liming of Alberta soils to counteract acidification will become a common practice. The average input of atmospheric acid forming substances is probably less than five percent of acidity resulting from fertilizer inputs. Thus, the costs of liming to counteract acid deposition as compared to costs to counteract fertilizer acid inputs are very low. The deposition on land adjacent to emitters may be relatively high, however, and continued research and monitoring would be required to determine actual deposition rates and to develop appropriate ameliorative measures.
12. Although liming practices can neutralize acidity in agricultural soils, this would be impractical in range and forest land. The counteracting capability of these lands will be solely dependent on base recycling by vegetation, buffer capacity and other properties of the soil.
13. Although there is potential for degradation of soils due to acidic deposition in the long term, the nutritional benefits of N and S to vegetation may partially compensate for these effects.
14. The deposition of SOx and NOx on soil surfaces and the initial interactions that occur were briefly reviewed. Studies on atmospheric deposition of SO_2-S in Alberta have indicated that up to 50 kg ha^{-1} can be deposited in less than a year. There have been reports of lowered soil pH attributable to S deposition as well as reports concluding that there is insufficient evidence linking acidification to industrial sulphur emissions. Mechanisms and forms of SO_2 and NOx sorption and other reactions have not been studied to a great extent. Some general conclusions from Alberta studies are that SO_2-S sorption does occur, although reported levels have been questioned, and that soil pH may be lowered. However, it is also recognized that pH alone is not a reliable measure of changes resulting from acid deposition. Thus, measures of other soil properties and processes are required to assess acid deposition impacts.

15. It is generally recognized that water dynamics and landscape processes will influence the fate of acid forming substances in soils. Soil moisture movement, leaching events related to episodic precipitation events, snowmelt, erosion, and other factors must be considered in assessing acid deposition impacts on soil as well as on water resources.

16. Several soil effects resulting from acid inputs have been experimentally shown, but results of long-term studies showing a reduction in productivity are still inconclusive.

17. An overview of the general properties, formation, and distribution of soils in Alberta was prepared to provide some generalized information for relating degrees of sensitivity and predicted responses to acidic deposition. All of the soil orders described in the Canadian soil classification system are found in Alberta. Descriptions of representative profiles from each of the orders were provided; some of these were then used in following sections in modelling exercises to predict soil responses to acidic inputs.

18. Sensitivity ratings of soils were briefly reviewed. The production of a soil sensitivity map and report is the objective of another concurrent project. The following briefly summarizes the ratings of soil orders in Alberta:

    Chernozemic soils generally have low sensitivity to acidification. Sandy Chernozemics associated with Regosols have high sensitivity. Luvisolic soils are generally considered to be moderately sensitive to acidification. Sandy Luvisols are highly sensitive.

    Solonetzic soils are generally moderately sensitive to acidification. Areas of Black Solods in the Peace River area, however, have low sensitivity due to relatively high buffering capacity.

    Brunisolic soils are mainly rated as highly sensitive. The Dystric Brunisols on sandy materials in northeastern Alberta are considered to be among the most sensitive soils in the province. Sandy Eutric Brunisols are also highly sensitive, but those developed on finer materials in the foothills and mountain regions are considered to have low sensitivity.

    Organic soils are mainly considered to be highly sensitive since many of them are mesotrophic and are susceptible to base loss and pH reduction. Eutrophic peatlands in and adjacent to the Peace River delta have high buffering capacity and therefore have low sensitivity.

    Organic Cryosols are considered to have low sensitivity since they are already highly acidic and further acid inputs would not alter their characteristics significantly.

    Podzolic soils do not occur extensively and are generally grouped with Brunisolic soils. Podzolic soils may have some sulphate sorbtion capacity which can moderate effects of acidification, at least in the short term.

    Gleysolic soils are mainly considered to have low sensitivity due to base input from surface and ground water discharge.

Regosolic soils are considered to be highly sensitive to acidification if they are sandy and non-calcareous. Gleyed Regosols of the Peace River delta and similar regions elsewhere have low sensitivity because they are generally rich in organic matter and are commonly calcareous.

19. An assessment of possible responses of different Alberta soils to acidic deposition was made by three methods, namely review of sensitivity ratings, qualitative description of possible processes, and application of a dynamic model of soil response to acid inputs. The modelling approach is probably the most powerful of these because it provides quantification of responses over specified periods of time.

20. A semiempirical model developed at the University of Minnesota (Bloom and Grigal 1985) was used to simulate response to acid inputs of a few selected soils. The model utilizes relationships among soil pH, base saturation, chemical activity of soil solution Al, and acidity constants. Model inputs include time, precipitation, evapotranspiration, wetfall, dryfall, and soil chemical parameters. The major outputs are changes in pH, base saturation, and soil solution Al over time.

21. Several conservative assumptions are made in the model of Bloom and Grigal (1985) and, as a consequence, results of simulations are more severe than can realistically be expected. That is, rates of change that are calculated are maximal rates.

22. Results of simulations verified that coarse-textured soils in each of the soil orders are the most sensitive to acid deposition. The effect of deposition of substances generating the equivalent of 0.1 kmol$(H^+)ha^{-1}$ y^{-1} was minimal in all soils except a very sandy Brunisol from northeastern Alberta in which changes occurred rapidly. The effect of deposition at a rate of 1 kmol $(H^+)ha^{-1}$ y^{-1} was significant over different periods of time in all soils. Significant reduction in pH and base saturation occurred in coarse-textured soils within 100 years of simulation. Luvisolic soils were strongly affected; they behave similarly to sandy soils due to low pH and CEC in their Ae horizons. Increase of solution Al concentrations to toxic levels occurred in Luvisols and Brunisols with initially low pH values. The simulation results suggested that the current status of Al in foothill soils should be examined in relation to toxic effects on vegetation.

23. Use of the model proved to be a powerful tool for predicting soil response to acid deposition. The output of the model provides a means of comparing soils and could be used to rank soils as to relative sensitivities to acidic deposition. However, it was found that there is inadequate data for Alberta soils for some of the inputs required by the model. Thus, continued work in developing a suitable model, in gathering soils data, and in investigating relationships among properties (e.g., between pH and base saturation) of Alberta soils is required.

7. RECOMMENDATIONS

Some of the objectives of the Acid Deposition Research Program (ADRP) are: (1) to provide a comprehensive understanding of the effects and consequences of acid-forming gases on the environment; and (2) to provide a scientific basis for sound, long-term environmental management and regulatory control with respect to acid-forming gases (Alberta Government/Industry Acid Deposition Research Program 1984). To satisfy these objectives with regard to the soils component of the ADRP, a number of recommendations are made which fall into three broad groups. First, recommendations directed towards providing a capability for predicting the effects of acid deposition on soils are made. Secondly, a number of measures designed to help resolve deficiencies in understanding the consequences of deposition of acidic and acid forming substances on soils are suggested. These recommendations primarily address the need to gain more knowledge and understanding of properties and processes of soils subject to acid deposition. Efforts are required in both of these areas to enable development of management and regulatory control procedures, and of methods for counteracting or preventing degradation of soils. A third group of recommendations addresses priorities among different kinds of soils.

The first group of recommendations addresses the need to develop predictive capability of the responses of soils to inputs of acidic and acid forming substances from the atmosphere. It was concluded that application of dynamic models is a powerful tool for predicting responses and ranking sensitivities of soils. However, there is insufficient information about the suitability of existing models in terms of assumptions, processes, and input data required for soils of Alberta.

1. It is recommended that the long-term implications of acid deposition be investigated through development, or selection, and application of numerical models. Development of soil response models should be within the context of a general ecosystem model; that is, the model should be developed so as to interface with other ecosystem models which will describe impacts on various components of terrestrial and aquatic ecosystems. To this end, a literature review should be undertaken to determine model requirements for application to Alberta soils, and to evaluate the suitability of existing, published models for this purpose.
2. It is recommended that a model or models be selected or developed for predicting responses of Alberta soils to acid deposition. Research should also be carried out to provide appropriate data wherever information is insufficient for developing model codes representing soil properties, interrelationships, and processes.
3. It is recommended that model simulations of base cation mobilization, leaching, and other processes be made for a range of soil types, and that the model performance be evaluated through field and laboratory studies.
4. It is recommended that current soil sensitivity ratings be evaluated and updated using the results of simulations of soil responses to acid inputs.

It was concluded in this review that there exist many gaps in our basic knowledge of the potential effects of acidic and acid forming substances on soils, as well as in our knowledge of various soil properties and processes necessary for understanding and estimating the impacts. The following second group of recommendations addresses the need to improve the knowledge and information base about acid deposition impacts on soils. This information will be especially necessary for refinement of models as indicated in the previous recommendations.

5. With regard to initial atmospheric SO_2/NOx-soil interactions, it is recommended:
   a. that measurement of SO_2, NOx, and other deposition to soils in the field be continued and possibly expanded;
   b. that functional relationships between SO_2/NOx and soils be determined by laboratory studies such as SO_2/NOx adsorption isotherm determinations for different soils under varying conditions of moisture content, pH, and other parameters;
   c. that SO_2/NOx-soil reactions, products, organic and inorganic forms, transformations, and transport be determined; and
   d. that soil microbiological processes involving SO_2, NOx, and other atmospherically deposited substances be investigated.
6. With regard to potential for changes in acidity and base status, and the possible consequences in relation to nutrient status and throughflow to streams and lakes, it is recommended:
   a. that the relationships among pH, base saturation, lime potential, cation selectivity, and other solution-solid interface properties of Alberta soils be determined;
   b. that the buffering capacities of Alberta soils be investigated by determination of titration curves and other means;
   c. that weathering processes, rates, and products in Alberta soils be investigated, and the role of weathering in acid neutralization be evaluated;
   d. that sulphate sorption mechanisms and capacities be evaluated and related to cation mobility and leaching; and
   e. that atmospheric dust, and dissolved and entrained substances in precipitation, be monitored and evaluated in terms of acid neutralizing capacity.
7. It is recommended that the solubilization and movement of Al, Mn, and heavy metals, which are potentially toxic to organisms, be investigated within the framework of acidification and base cation studies suggested in point 6 above. Examination of the effects of soluble organic materials on the forms and levels of these elements will be necessary in these studies.
8. It is recommended that alterations in biogeochemical cycles resulting from acidic inputs be examined. Effects such as reduction in nitrification and denitrification rates, accumulation of nutrient elements in biomass, effects of sulphate on P solubilization, and various other processes require investigation. Most of these involve microbiological activities in soils. However, abiotic factors such as weathering products, base leaching, Al and heavy metal mobilization, and others are essential inputs in nutrient cycling investigations.

9. It is recommended that research on quantification of moisture regimes in different soils and landscapes be carried out. The purpose of this is to determine the proportion of influent solution that can react with soil material, and to determine moisture budgets, flow paths, and processes during specific events such as heavy rainfalls and snowmelt. Knowledge of these various aspects of soil moisture is necessary for predicting proportions of acidic inputs which actually react with soil, predicting their residence times, and predicting proportions which flow into groundwater or surface water bodies. This aspect would interface with research in the hydrological component of the ADRP program. The application of soil moisture and watershed system models would be an integral component of this activity.

A third group of recommendations addresses needs of specific groups of soils:

10. It is recommended that particular attention be given to research into highly sensitive soils such as the sandy Brunisols of northeastern Alberta, soils in areas of high deposition rates of acidic and acid forming substances, and soils for which little information is available, especially the Brunisols and Luvisols of the foothills region. This recommendation is made with a sense of urgency, recognizing the high susceptibility of certain soils and the inadequacy of information about them.
11. It is recommended that research into the effects of fertilizer practices on acidification of soils be continued. Such research would necessarily include the effects of different types of fertilizers on different soil types, and would include research into ameliorative measures such as liming.
12. It is recommended that research into the effects of acid deposition on peatlands be carried out. Peatlands are a large and vital part of the Alberta landscape forming linkages beteen aquatic and terrestrial ecosystems. Little is known about the response of peatlands to acid deposition and about subsequent effects on ground and surface water properties. Organic soils differ from mineral soils in many ways and therefore require special consideration. A first step in peatland studies should be a review and compilation of existing information relevant to chemistry, hydrology, and biology and the effects of acid deposition on these. Subsequent research and monitoring programs would be based on the recommendations of such a review.

The suggested priority of research needs is indicated in the summary of recommendations in Table 46. High priority is given to recommendations related to modelling. These are listed in order of precedence and, therefore, recommendation 1 has the highest priority since it must be accomplished first. Priorities in the second group of recommendations are based on the need for further refinements in soil effects modelling, but there is no required order of precedence. With regard to different kinds of soils, highest priority is given to those which appear to be in greatest danger of being affected by acid deposition.

Table 46. Summary of recommendations for research on acid deposition effects on soils in Alberta.

Item	Subject	Knowledge Gap	Recommended Program	Priority
I.	Modelling - in order of precedence			
1.	Model review	Models applicable to Alberta soils and ecosystems	Literature review and comparison of available models	High
2.	Model inputs	Codes representing soil properties, interrelationships, and processes	Literature and data review with limited laboratory investigations	High
3.	Model validation	Performance of models	Compare data from literature and from lab and field experiments with model simulations	High
4.	Model application	Quantification of soil sensitivity	Apply model to soil units in sensitivity maps	High
II.	Expansion of Soils Information Base			
5.	SO_2/NOx-soil interactions	Functional relationships between SO_2/NOx and soil	Determine sorption mechanisms, and products in field and laboratory experiments	High
6.	Factors affecting soil acidity and buffering	Little information available on pH-exchange complex relationships, weathering, sulphate sorption, and external base inputs	Laboratory and field experimentation	High

continued...

Table 46 (Concluded).

Item	Subject	Knowledge Gap	Recommended Program	Priority
7.	Aluminum and heavy metals	Levels and toxicity of Al and heavy metals to vegetation	Survey levels in acid soils and determine responses to increased acidity in field and lab experiments	High
8.	Biogeochemical cycling	Nutrient cycling responses to acid deposition	Data collection and experimentation at field sites, coupled with modelling	Medium
9.	Soil moisture budgets	Information about moisture budgets, transport, and processes during rainfall and snowmelt	Data collection at field sites, coupled with modelling	Medium
III.	Approaches to Different Ecosystems and Soil Types			
10.	Sensitive mineral soils	Degree of susceptibility of sensitive soils to acid deposition	Carry out above recommendations on highly sensitive soils as identified in the soil sensitivity map of Alberta	High
11.	Fertilization	Degree and extent, mechanisms, and remedial measures of soil acidification due to fertilization	Program involving monitoring, experimentation, and modelling	Medium
12.	Peatlands	Responses to acid deposition	Program involving monitoring, experimentation, and modelling. Should interface with lake-watershed modelling.	Medium

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9. GLOSSARY

adsorption complex
The group of substances in the soil capable of adsorbing water and nutrients.

aeration, soil
The process by which air in the soil is replaced by air from the atmosphere. The rate of aeration depends largely on the volume and continuity of pores in the soil.

aggregate, soil
A group of soil particles cohering so as to behave mechanically as a unit.

alkalization
The process whereby the exchangeable sodium content of a soil is increased.

alluvium
A general term for all detrital material deposited or in transit by streams, including gravel, sand, silt, clay, and all variations and mixtures of these.

anion
An ion carrying a negative charge of electricity. The common organic soil anions are bicarbonate, carbonate, sulphate, chloride and hydroxyl.

anion exchange capacity
The total amount of exchangeable anions that a soil can adsorb. It is expressed as $\mathrm{cmol}(-)\mathrm{kg}^{-1}$ of soil or other adsorbing material such as clay.

anthropogenic
Man-made or man-modified materials, including those associated with mineral exploitation and waste disposal.

argillic
Pertaining to a soil horizon in which layer-lattice silicate clays have accumulated by illuviation to a significant extent.

available nutrient
That portion of any element or compound in the soil that can readily be absorbed and assimilated by growing plants.

base saturation percentage
The extent to which the adsorption complex of a soil is saturated with exchangeable cations other than hydrogen and aluminum.

bedrock
The solid rock underlying soils and the regolith in depths ranging from zero (where exposed to erosion) to several hundred feet.

bog
A peat-covered area or peat-filled wetland, generally, with a high water table. The water table is at or near the surface. The surface is often raised, or level with the surrounding wetlands, and is virtually unaffected by the nutrient-rich ground waters from the surrounding mineral soils. Hence, the ground water of the bog is generally acidic and low in nutrients. The dominant peat materials are sphagnum and forest peat underlain, at times, by fen peat.

boulders
Stones which are larger than 60 cm in diameter.

boundary, horizon
The contact plane between soil horizons which is described by indicating its distinctness and form.

Distinctness

abrupt:	less than 2.5 cm wide
clear:	2.5 to 6 cm wide
gradual:	6 to 13 cm wide
diffuse:	more than 13 cm wide

Form
smooth: nearly a plane
wavy: pockets are wider than deep
irregular: pockets are deeper than wide
broken: some parts are unconnected

bulk density, soil
The mass of dry soil per unit bulk volume.

calcareous classes
The calcareous classes, expressed in terms of $CaCO_3$ equivalent are: weakly (6%), moderately (6-15%), strongly (16-25%), very strongly (26-40%), and extremely (40%).

calcareous soil
Soil containing sufficient calcium carbonate, often with magnesium carbonate, to effervesce visibly when treated with cold 0.1N hydrochloric acid.

calcium carbonate equivalent
The total inorganic carbon content of soil material expressed in terms of percent calcium carbonate ($CaCO_3$).

cation
An ion carrying a positive charge of electricity. The common soil cations are calcium, magnesium, sodium, potassium, and hydrogen.

cation exchange
The interchange between a cation in solution and another on the surface of any surface-active material in the soil such as clay or organic matter.

cation exchange capacity (total exchange capacity)
The total amount of exchangeable cations that a soil can adsorb. In SI units, it is expressed in centimole positive charge per kg of soil (cmol(p+)/kg).

chroma
The relative purity, strength, or saturation of a colour. It is directly related to the dominance of the determining wavelength of light.

clay
(i) As a particle-size term: a size fraction less than 0.002 mm in equivalent diameter, or some other limit (geology and engineering). (ii) As a rock term: a natural, earthy, fine grained material that develops plasticity with a small amount of water. (iii) As a soil term: a textural class. See also texture, soil. (iv) As a soil separate: a material usually consisting largely of clay minerals but commonly also of amorphous free oxides and primary minerals.

clay films (skins)
Coatings of oriented clays on the surface of soil peds and mineral grains, with a phyllosilicate structure.

clay mineral
Finely crystalline hydrous aluminum silicates and hydrous magnesium silicates with a phyllosilicate structure.

coarse fragments
Rock or mineral fragments greater than 2.0 mm in diameter.

cobbly
Containing appreciable quantities of rounded or subrounded coarse rock or mineral fragments 8 to 25 cm in diameter. "Angular cobbly" is used when the fragments are less rounded.

colloid, soil
Organic or inorganic matter having very small particle size and a correspondingly large surface area per unit of mass. Most colloidal particles are too small to be seen with the ordinary compound microscope.

colluvial
Massive to moderately well-stratified, non-sorted to poorly sorted sediments with any range of particle sizes from clay to boulders and blocks that have been deposited at the base of slopes due to direct, gravity-induced movement.

colour
See Munsell colour system.

consistence
(i) The resistance of a material to deformation or rupture. (ii) The degree of cohesion or adhesion of the soil mass. Terms used for describing consistence at various soil moisture contents are: *wet soil* - nonsticky, slightly sticky, sticky, and very sticky; *moist soil* - loose, very friable, friable, firm, and very firm; *dry soil* - loose, soft, slightly hard, hard, very hard, and extremely hard.

control section, soil
The vertical section upon which the taxonomic classification of soil is based. The control section usually extends to a depth of 100 cm in mineral materials and to 160 cm in organic materials.

cryoturbation
Frost action, including frost heaving.

delta
The accumulation of sediments where a stream empties into a body of quiet water, resulting in the building out of the shoreline.

deposition
The accumulation of material left in a new position by a natural transporting agent such as water, wind, ice or gravity; or by the activity of man.

drainage
The removal of excess surface water or groundwater from land by natural runoff and percolation, or by means of surface or subsurface drains. Soil drainage classes are defined in terms of available water storage capacity (AWSC) and source of water, as follows:

very rapidly drained
Water is removed from the soil very rapidly in relation to supply. Excess water flows downward very rapidly if underlying material is pervious. There may be very rapid subsurface flow during heavy rainfall provided there is a steep gradient. Soils have very low AWSC (usually 2.5 cm) within the control section and are usually coarse textured, shallow, or both. Water source is precipitation.

rapidly drained
Water is removed from the soil rapidly in relation to supply. Excess water flows downward if underlying material is pervious. Subsurface flow may occur on steep gradients during heavy rainfall. Soils have low AWSC (2.5 to 4 cm) within the control section, and are usually coarse textured, or shallow, or both. Water source is precipitation.

well drained
Water is removed from the soil readily but not rapidly. Excess water flows downward rapidly into underlying pervious material or laterally as subsurface flow. Soils have intermediate AWSC (4 to 5 cm) within the control section, and are generally intermediate in texture and depth. Water source is precipitation. On slopes subsurface flow may occur for short durations but additions are equalled by losses.

moderately well drained
Water is removed from the soil somewhat slowly in relation to supply. Excess water is removed somewhat slowly due to low perviousness, shallow water table, lack of gradient, or some combination of these. Soils have intermediate to high AWSC (5 to 6 cm) within the control section and are usually medium to fine textured. Precipitation is the dominant water source in medium to fine textured soils; precipitation and significant additions by subsurface flow are necessary in coarse textured soils.

imperfectly drained
Water is removed from the soil sufficiently slowly in relation to supply to keep the soil wet for a significant part of the growing season. Excess water moves slowly downward if precipitation is the major supply. If subsurface water or groundwater, or both, are the main sources, flow rate may vary but the soil remains wet for a significant part of the growing season. Precipitation is the main source if AWSC is high; contribution by subsurface flow or groundwater flow, or both, increases as AWSC decreases. Soils have a wide range in available water supply, texture, and depth, and are gleyed phases of well-drained subgroups.

poorly drained
Water is removed so slowly in relation to supply that the soil remains wet for a comparatively large part of the time the soil is not frozen. Excess water is evident in the soil for a large part of the time. Subsurface flow, groundwater flow, or both, in addition to precipitation are the main water sources; there may also be perched water tables with precipitation exceeding evapotranspiration. Soils have a wide range in AWSC, textures and depths, and are gleyed subgroups, Gleysols, and Organic soils.

very poorly drained
Water is removed from the soil so slowly that the water table remains at or on the surface for the greater part of the time the soil is not frozen. Excess water is present in the soil for the greater part of the time. Groundwater flow and subsurface flow are the major water sources. Precipitation is less important except where there is a perched water table with precipitation exceeding evapotranspiration. Soils have a wide range in ASWC, texture, and depth, and are either Gleysolic or Organic.

drift, glacial
Rock debris transported by glaciers and deposited either directly from the ice or from the meltwater.

dune
A mound or ridge of sand piled up by the wind.

duric
Pertaining to a subsurface soil horizon cemented by silica.

edaphic
(i) Of or pertaining to the soil. (ii) Resulting from or influenced by factors inherent in the soil or other substrate, rather than by climatic factors.

eluvial horizon
A soil horizon that has been formed by the process of eluviation.

eluviation
The transportation of soil material in suspension or in solution within the soil by the downward or lateral movement of water.

eolian
Sediments that have been transported and deposited by wind action and which generally consist of medium to fine sand and coarse silt particle sizes. They are generally well sorted and poorly compacted, may show internal cross bedding or ripple structures, or may be massive.

erosion
The wearing away of the land surface by running water, wind, ice, or other geological agents, including such processes as gravitational creep.

eutrophic
Containing abundant plant nutrients such as nitrogen, potassium, phosphorus, and calcium.

evapotranspiration
The combined loss of water from a given area and during a specific period of time, by evaporation from the soil surface and by transpiration from plants.

exchangeable cation
A cation that is held by the adsorption complex of the soil and is easily exchanged with other cations of neutral salt solutions.

fen
A fen is a peat-covered or peat-filled wetland with a high water table which is usually at or above the surface. The peat materials are derived primarily from sedges and brown mosses with inclusions of partially decayed stems of shrubs formed in an eutrophic environment due to the close association of the material with mineral-rich waters.

fen peat
Peat consisting mainly of the remains of sedges, grasses, reeds, and brown mosses.

fertility, soil
The status of a soil in relation to the amount and availability to plants of elements necessary for plant growth.

fiber, rubbed or unrubbed
The organic material retained on a 100-mesh sieve (0.15 mm) either with or without rubbing, except for wood fragments that cannot be crushed in the hand and are larger than 2 mm in the smallest dimension.

fibric
The least decomposed state of all organic materials. There is a large amount of well-preserved fiber that is readily identifiable as to botanical origin. Fibers retain their character upon rubbing.

floodplain
The land bordering a stream, built up of sediments from overflow of the stream and subject to inundation when the stream is at flood stage.

fluvial, glaciofluvial
Sediments mainly composed of sand and gravel which have been transported and deposited by streams and rivers and which are commonly moderately to well sorted and stratified.

forb - A herbaceous plant which is not a grass, sedge, or rush.

forest peat
Peat materials derived mainly from trees, such as black spruce, and from ericaceous shrubs, and feathermosses.

fragic
Pertaining to a subsoil horizon with high bulk density, seemingly cemented when dry, but when moist showing a moderate to weak brittleness.

frost free period
The period or season of the year between the last spring frost and the first autumn frost.

genesis, soil
The mode of origin of the soil, especially the processes or soil forming factors responsible for development of the solum from unconsolidated parent material.

genetic material
Material classified according to its origin or genesis. Classes include anthropogenic, colluvial, eolian, fluvial (glaciofluvial), lacustrine (glaciolacustrine), morainal, undifferentiated, bog, fen, swamp, bedrock, and ice (q.v.).

gravel
Rock or mineral fragments 2 mm to 8 cm in diameter.

gravelly
Containing appreciable quantities of rounded or subrounded coarse rock or mineral fragments 2 mm to 8 cm in diameter. "Angular gravelly" is used when the fragments are less rounded.

great group
A category in the Canadian system of soil classification. It is a taxonomic grouping of soils having certain morphological features in common and a similar pedogenic environment.

groundwater
Water that is passing through or standing in the soil and the underlying strata in the zone of saturation. It is free to move by gravity.

growing season
Period with soil temperatures over 5 degrees Celsius at a depth of 50 cm.

herb
Any flowering plants except those developing persistent woody bases and stems above ground.

horizon, soil
A layer of soil or soil material approximately parallel to the land surface; it differs from adjacent genetically related layers in properties such as colour, structure, texture, consistence, and chemical, biological, and mineralogical composition. A list of the designations and some of the properties of soil horizons and layers follows. More detailed definitions of some horizons and layers may be found in The System of Soil Classification for Canada.

Organic layers contain 17% or more organic carbon. Two groups of these layers are recognized:

O - An organic layer developed mainly from mosses, rushes, and woody materials.

Of - The least decomposed organic layer, containing large amounts of well-preserved fiber, and called the fibric layer.

Om - An intermediately decomposed organic layer containing less fiber than an Of layer and called the mesic layer.

Oh - The most decomposed organic layer, containing only small amounts of raw fiber and called the humic layer.

L-F-H - Organic layers developed primarily from leaves, twigs, and woody materials, with a minor component of mosses.

L - The original structures of the organic material are easily recognized.
F - The accumulated organic material is partly decomposed.
H - The original structures of the organic material are unrecognizable.

Mineral horizons and *layers* contain less than 17% organic carbon.

A - A mineral horizon formed at or near the surface in the zone of removal of materials in solution and suspension, or maximum in situ accumulation of organic carbon, or both.
B - A mineral horizon characterized by one or more of the following:
  (1) An enrichment in silicate clay, iron, aluminum, or humus.
  (2) A prismatic or columnar structure that exhibits pronounced coatings or stainings associated with significant amounts of exchangeable solutions.
  (3) An alteration of hydrolysis, reduction, or oxidation to give a change in colour or structure from the horizons above or below, or both.
C - A mineral horizon comparatively unaffected by the pedogenic processes operative in A and B, except gleying, and the accumulation of carbonates and more soluble salts.
R - Underlying consolidated bedrock that is too hard to break with the hands or to dig when moist.

Roman numerals are prefixed to horizon designations to indicate unconsolidated lithologic discontinuities in the profile. Roman numeral I is understood for the uppermost material and usually is not written. Subsequent contrasting materials are numbered consecutively in the order in which they are encountered downward, that is, II, III, and so on.

Lowercase Suffixes

e - A horizon characterized by removal of clay, iron, aluminum, or organic matter alone or in combination and higher in colour value by one or more units when dry than an underlying B horizon. It is used with A(Ae).

g - A horizon characterized by gray colours, or prominent mottling indicative of permanent or periodic intense reduction, or both; for example, Aeg, Btg, Bg, or Cg.

h - A horizon enriched with organic matter.

Ah - An A horizon of organic matter accumulation. It contains less than 17% organic carbon. It is one Munsell unit of colour value darker than the layer immediately below, or it has at least 0.5% more organic carbon than the IC, or both.

Ahe - This horizon has been degraded, as evidenced by streaks and splotches of light and dark gray material and often by platy structure.

j - This is used as a modifier of suffixes e, g, n, and t to denote an expression of, but failure to meet, the specified limits of the suffix it modifies; for example, Aej is an eluvial horizon that is thin, discontinuous, or faintly discernible.

k - Presence of carbonate.

m - A horizon slightly altered by hydrolysis, oxidation, or solution, or all three, to give a change in colour, or structure, or both.

t - A horizon enriched with silicate clay, as indicated by a higher clay content (by specified amounts) than the overlying eluvial horizon, a thickness of at least 5 cm, oriented clay in some pores, or on ped surfaces, or both, and usually a higher ratio of fine (less than 0.2 m) to total clay than in the IC horizon.

z - A perennially frozen layer.

hue

The aspect of colour that is determined by the wavelengths of light, and changes with the wavelength. Munsell hue notations indicate the visual relationship of a colour to red, yellow, green, blue, or purple, or an intermediate of these hues.

humic

Highly decomposed organic material. Small amounts of fiber are present that can be identified as to their botanical origin. Fibers can be easily destroyed by rubbing.

humification

The processes by which organic matter decomposes to form humus.

humus

(1) The fraction of the soil organic matter that remains after most of the added plant and animal residues have decomposed. It is usually dark coloured. (2) Humus is also used in a broader sense to designate the humus forms referred to as forest humus. (3) All the dead organic material on and in the soil that undergoes continuous breakdown, change and synthesis.

igneous rock

Rock formed by solidification from a molten or partially molten state.

illuvial horizon

A soil horizon in which material carried from an overlying layer has been precipitated from solution or deposited from suspension as a layer of accumulation.

illuviation

The process of depositing soil material removed from one horizon in the soil to another, usually from an upper to a lower horizon in the soil profile. Illuvial substances include silicate clay, hydrous oxides of iron and aluminum, and organic matter.

impeding horizon

A horizon which hinders the movement of water by gravity through soils.

infiltration

The downward entry of water into the soil.

lacustrine, glaciolacustrine
Materials that either have settled from suspension in bodies of standing fresh water or have accumulated at their margins through wave action. The sediments are generally stratified fine sand, silt, and clay deposited on lake beds, or moderately well-sorted and stratified sand and coarser materials that are beach and other nearshore sediments transported and deposited by wave action.

landforms
The various shapes of the land surface resulting from a variety of actions such as deposition or sedimentation (eskers, lacustrine basins), erosion (gullies, canyons), and earth crust movements (mountains). Landforms are considered to represent two basic attributes, genetic material and surface expression (q.v.).

leaching
The downward movement within the soil of materials in solution.

lessivage
The washing in suspension of fine clay and lesser amounts of coarse clay and fine silt down cracks and other voids in a soil body.

lime (in soil)
A soil constituent consisting principally of calcium carbonate, and including magnesium carbonate, and perhaps the oxide and hydroxide of calcium and magnesium.

limestone
A sedimentary rock composed of calcium carbonate.

lithic layer
Bedrock under the control section of a soil. In Organic soils, bedrock occurring within a depth of between 10 cm and 160 cm from the surface.

marsh
A marsh is a mineral or a peat-filled wetland which is periodically inundated by standing or slowly moving nutrient-rich water. Surface water levels may fluctuate seasonally, with declining levels exposing drawndown zones of matted vegetation or mud flats. The substratum usually consists dominantly of mineral material, although some marshes are associated with peat deposits.

matrix, soil
The main soil constituent or material that encloses other soil features, for example, concretions embedded in a fine grained matrix.

mesic
Organic material in an intermediate stage of decomposition. Intermediate amounts of fiber are present that can be identified as to their botanical origin.

mesotrophic
Containing a moderate amount of plant nutrients.

metamorphic rock
Rock derived from pre-existing rocks but that differs from them in physical, chemical and mineralogical properties as a result of natural geological processes, principally heat and pressure, originating within the earth.

microclimate
(i) The climate of a small area resulting from the modification of the general climate by local differences in elevation or exposure. (ii) The sequence of atmospheric changes within a very small region.

microrelief
Small scale, local differences in relief, including mounds, swales, or hollows.

minerotrophic
A supply of water to vegetation originally derived from mineral soils or rocks but sometimes via lakes or rivers as intermediates; it may be eutrophic, mesotrophic, or oligotrophic.

mor
A humus form of well drained to imperfectly drained sites consisting of organic horizons sharply delineated from the mineral soil.

morainal
Sediment that is generally well compacted, nonstratified, and heterogeneous in particle size composition, and which has been deposited directly from glacial ice without modification by any intermediate agent.

moraine
A mound, ridge or other distinct accumulation of unsorted, unstratified glacial drift, predominantly till, deposited chiefly by direct action of glacial ice in a variety of topographic landforms.

morphology, soil
The physical constitution, particularly the structural properties, of a soil profile as exhibited by the kinds, thickness and arrangement of the horizons in the profile; and by the texture, structure, consistence, and porosity of each horizon.

mottling
Spotting and blotching of different colour or shades of colour interspersed with the dominant colour.

muck
Fairly well-decomposed organic soil material relatively high in mineral content, dark in colour, and accumulated under conditions of imperfect drainage.

mull
Zoogenous forest humus form consisting of an intimate mixture of well humified organic matter and mineral soil with gradual transition to the horizon underneath.

Munsell colour system
A colour designation system specifying the relative degrees of the three simple variables of colour: hue, value, and chroma (q.v.).

muskeg
A North American term frequently employed for peatland (organic terrain).

nonsoil
The aggregate of surficial materials that do not meet the definition of soil.

oligotrophic
Containing a small amount of plant nutrients.

ombrotrophic
A supply of nutrients exclusively from rain water (including snow and atmospheric fall-out), therefore making nutrition extremely oligotrophic often in an unbalanced way.

order, soil
A category in the Canadian system of soil classification. All the soils within an order have one or more characteristics in common.

organic carbon, soil
The percent by weight of carbon in organic forms in soil materials, determined by the difference between total carbon (determined by dry combustion) and inorganic carbon (determined by acid dissolution).

organic matter, soil
The organic fraction of the soil; includes plant and animal residues at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by the soil population. It is estimated by multiplying the soil organic carbon content by 1.724.

Organic soil

An order of soils that have developed dominantly from organic deposits. The majority of Organic soils are saturated for most of the year, unless artificially drained, but some of them are not usually saturated for more than a few days. They contain 17% or more organic carbon, and:

1. if the surface layer consists of fibric organic material and the bulk density is less than 0.1 (with or without a mesic or humic Op less than 15 cm thick), the organic material must extend to a depth of at least 60 cm; or
2. if the surface layer consists of organic material with a bulk density of 0.1 or more, the organic material must extend to a depth of at least 40 cm; or
3. if a lithic contact occurs at a depth shallower than stated in 1. or 2. above, the organic material must extend to a depth of at least 10 cm.

orstein

An indurated layer in the B horizon of Podzols in which the cementing material consists of illuviated sesquioxides and organic matter.

orthic

A subgroup referring to the modal or central concept of various great groups in the Brunisolic, Chernozemic, Cryosolic, Gleysolic, Luvisolic, Podzolic, and Regosolic orders of the Canadian system of soil classification.

paludification

Formation of mire systems over previously forested land, grassland or even bare rock, due to climatic or autogenic processes. The literal meaning is "swamping".

parent material

The unconsolidated and more or less chemically weathered mineral or organic matter from which the solum of a soil has developed by pedogenic processes.

particle-size analysis

The determination of the various amounts of the different separates in a soil sample, usually by sedimentation, sieving, micrometry, or combinations of these methods. Has been called grain-size analysis or mechanical analysis.

particle-size classes (for soil families and parent materials)

Groupings of particle-size distribution of the whole soil or soil material including the coarse fraction. They are used for generalized descriptions of soils, and differ from texture which refers to the fine earth fraction (<2 mm) only. The classes are are described as follows:

Fragmental - Stones, cobbles and gravel, with too little fine earth to fill interstices larger than 1 mm.

Sandy-skeletal - Particles coarser than 2 mm occupy 35% or more by volume with enough fine earth to fill interstices larger than 1 mm; the fraction finer than 2 mm is that defined for the sandy particle-size class.

Loamy-skeletal - Particles 2 mm-25 cm occupy 35% or more by volume with enough fine earth to fill interstices larger than 1 mm; the fraction finer than 2 mm is that defined for the loamy particle-size class.

Clayey-skeletal - Particles 2 mm-25 cm occupy 35% or more by volume with enough fine earth to fill interstices larger than 1 mm; the fraction finer than 2 mm is that defined for the clayey particle-size class.

Sandy - The texture of the fine earth includes sands and loamy sands, exclusive of loamy very fine sand and very fine sand textures; particles 2 mm-25 cm occupy less than 35% by volume.

Loamy - The texture of the fine earth includes loamy very fine sand, very fine sand, and finer textures with less than 35% clay; particles 2 mm-25 cm occupy less than 35% by volume.

Coarse-loamy - A loamy particle size that has 15% or more by weight of fine sand (0.25-0.1 mm) or coarser particles, including fragments up to 7.5 cm, and has less than 18% clay in the fine earth fraction.

Fine-loamy - A loamy particle size that has 15% or more by weight of fine sand (0.25-0.1 mm) or coarser particles, including fragments up to 7.5 cm, and has 18-35% clay in the fine earth fraction.

Coarse-silty - A loamy particle size that has less than 15% of fine sand (0.25-0.1 mm) or coarser particles, including fragments up to 7.5 cm, and has less than 18% clay in the fine earth fraction.

Fine-silty - A loamy particle size that has less than 15% of fine sand (0.25-0.1 mm) or coarser particles, including fragments up to 7.5 cm, and has 18-35% clay in the fine earth fraction.

Clayey - The fine earth contains 35% or more clay by weight and particles 2 mm-25 cm occupy less than 35% by volume.

Fine-clayey - A clayey particle size that has 35-60% clay in the fine earth fraction.

Very-fine-clayey - A clayey particle size that has 60% or more clay in the fine earth fraction.

particle-size distribution

The amounts of the various soil separates in a soil sample, usually expressed as weight percentages.

peat

Material constituting peatlands, exclusive of live plant cover, consisting largely of organic residues accumulated as a result of incomplete decomposition of dead plant constituents under conditions of excessive moisture.

peatland

A general term for any tract covered with a layer of soil containing a high percentage of peat.

ped, soil

A unit of soil structure such as a prism, block, or granule, which is formed by natural processes.

pedogenic

Pertaining to the mode of origin of the soil, especially the processes or soil forming factors responsible for the development of the solum.

perched water table

A water table due to the "perching" of water on a relatively impermeable layer at some depth within the soil. The soil within or below the impermeable layer is not saturated with water.

percolation

The downward movement of water through saturated or nearly saturated soil.

permafrost

(i) Perennially frozen material underlying the solum. (ii) A perennially frozen soil horizon.

permafrost table

The upper boundary of permafrost, usually coincident with the lower limit of seasonal thaw.

permeability, soil

The ease with which gases and liquids penetrate or pass through a bulk mass of soil or a layer of soil. Because different soil horizons vary in permeability, the specific horizon should be designated.

pH, soil

The negative logarithm of the hydrogen-ion activity of a soil. The degree of acidity or alkalinity of a soil as determined by means of a glass, quinhydrone, or other suitable electrode or indicator at a specified moisture content or soil-water ratio, and expressed in terms of the pH scale.

pH-dependent cation exchange capacity

The difference between the effective cation exchange capacity and the cation exchange capacity of a soil measured at a pH higher than that of its natural value.

placic

Pertaining to a thin, black to dark reddish horizon cemented by iron, iron and manganese, or an iron-organic matter complex.

platy
Consisting of soil aggregates that have developed predominantly along the horizontal axes; laminated; flaky.

podzolization
A process of soil formation resulting in the genesis of Podzolic soils.

porosity, soil
The volume percentage of the total bulk not occupied by solid particles.

profile, soil
A vertical section of the soil through all its horizons and extending into the parent material.

reaction, soil
The degree of acidity or alkalinity of a soil, usually expressed as a pH value. Descriptive terms commonly associated with certain ranges in pH are: extremely acid, less than 4.5; very strongly acid, 4.5-5.0; strongly acid, 5.1-5.5; moderately acid, 5.6-6.0; slightly acid, 6.1-6.5; neutral, 6.6-7.3; slightly alkaline, 7.4-7.8; moderately alkaline, 7.9-8.4; strongly alkaline, 8.5-9.0; and very strongly alkaline, greater than 9.0.

relief
The elevations or inequalities of the land surface when considered collectively.

rock
Any naturally formed, consolidated or unconsolidated material, other than soil, composed of two or more minerals or occasionally of one mineral, and having some degree of chemical and mineralogic constancy.

saline soil
A nonalkali soil that contains enough soluble salts to interfere with the growth of most crop plants.

salinization
The process of salt accumulation in soil.

saturation extract
The extract from a soil sample that has been saturated with water.

separates, soil
Mineral particles, less than 2.0 mm in equivalent diameter, ranging between specified size limits. The names and size limits of separates recognized in pedology in Canada and the United States are: very coarse sand, 2.0 to 1.0 mm; coarse sand, 1.0 to 0.5 mm; medium sand, 0.5 to 0.25 mm; fine sand, 0.25 to 0.10 mm; very fine sand, 0.10 to 0.05 mm; silt, 0.05 to 0.002 mm; clay, less than 0.002 mm; and fine clay, less than 0.0002 mm.

series, soil
A category in the Canadian system of soil classification. This is the basic unit of soil classification, and consists of soils that are essentially alike in all major profile characteristics except the texture of the surface.

sesquioxide
A collective term for various iron and aluminum oxides and hydroxides.

shale
A laminated, detrital sedimentary rock in which the particles are predominantly of clay size.

slope classes

The description of an area or region in terms of the steepness of slopes. The slope classes and class limits, and descriptive terminology are:

Slope Class	Percent Slope	Approximate Degrees	Terminology
1	0 - 0.5	0	level
2	0.5 - 2.5	0.3 - 1.5	nearly level
3	2 - 5	1 - 3	very gentle slopes
4	6 - 9	3.5 - 5	gentle slopes
5	10 - 15	6 - 8.5	moderate slopes
6	16 - 30	9 - 17	strong slopes
7	31 - 45	17 - 24	very strong slopes
8	46 - 70	25 - 35	extreme slopes
9	71 - 100	35 - 45	steep slopes
10	100	45	very steep slopes

soligenous

Referring to peatlands with water percolating through them and carrying minerals into the peatland from outside sources.

solum, soil (plural = *sola*)

The upper horizons of a soil in which the parent material has been modified and in which most plant roots are contained. It usually consists of A and B horizons.

solution, soil

The aqueous liquid phase of the soil and its solutes consisting of ions dissociated from the surfaces of the soil particles and of other soluble materials.

stones

Rock fragments greater than 25 cm in diameter if rounded and greater than 38 cm along the greater axis if flat.

structure classes, soil

A grouping of soil structural units or peds on the basis of size. These are tabulated under structure types, soil.

structure grades, soil

A grouping or classification of soil structure on the basis of inter- and intra-aggregate adhesion, cohesion, or stability within the profile. Three grades of structure designated from 1 to 3 are:

(1) *weak* - poorly formed, indistinct peds, barely evident in place.

(2) *moderate* - well-formed distinct peds, moderately durable and evident, but not distinct, in undisturbed soil.

(3) *strong* - durable peds that are quite evident in undisturbed soil, adhere weakly to one another, withstand displacement, and become separated when the soil is disturbed.

structure, soil

The combination or arrangement of primary soil particles into secondary particles, units, or peds. These peds may be, but usually are not, arranged in the profile in such a manner as to give a distinctive characteristic pattern. The peds are characterized and classified on the basis of size, shape, and degree of distinctness into classes, types, and grades.

structure types, soil

A classification of soil structure based on the shape of the aggregates or peds and their arrangement in the profile. Structure types and classes are described in Table 47 and in Figure 22.

Table 47. Types, kinds and classes of soil structure.

Type	Kind	Class	Size (mm)
1. Structureless - no observable aggregation or no definite orderly arrangement around natural lines of weakness.	A. Single grain - loose incoherent mass of individual particles as in sands.		
	B. Amorphous (massive) - a coherent mass showing no evidence of any distinct arrangement of soil particles.		
2. Blocklike - soil particles arranged around a point and bounded by flat or rounded surfaces.	A. Blocky (angular blocky) - faces rectangular and flattened, vertices sharply angular.	Fine blocky	<10
		Medium blocky	10-20
		Coarse blocky	20-50
		Very coarse blocky	>50
	B. Subangular blocky - faces subrectangular, vertices mostly oblique, or subrounded.	Fine subangular blocky	<10
		Medium subangular blocky	10-20
		Coarse subangular blocky	20-50
		Very coarse subangular blocky	>50
3. Platelike - soil particles arranged around a horizontal plane and generally bounded by relatively flat horizontal surfaces.	A. Platy - horizontal planes more or less developed	Fine platy	<2
		Medium platy	2-5
		Coarse platy	>5
4. Prismlike - soil particles arranged around a vertical axis and bounded by relatively flat vertical surfaces.	A. Prismatic - vertical faces well defined and edges sharp.	Fine prismatic	<20
		Medium prismatic	20-50
		Coarse prismatic	50-100
		Very coarse prismatic	>100
	B. Columnar - vertical edges near top of columns not sharp. (Columns may be flat-topped, round-topped, or irregular.)	Fine columnar	<20
		Medium columnar	20-50
		Coarse columnar	50-100
		Very coarse columnar	>100

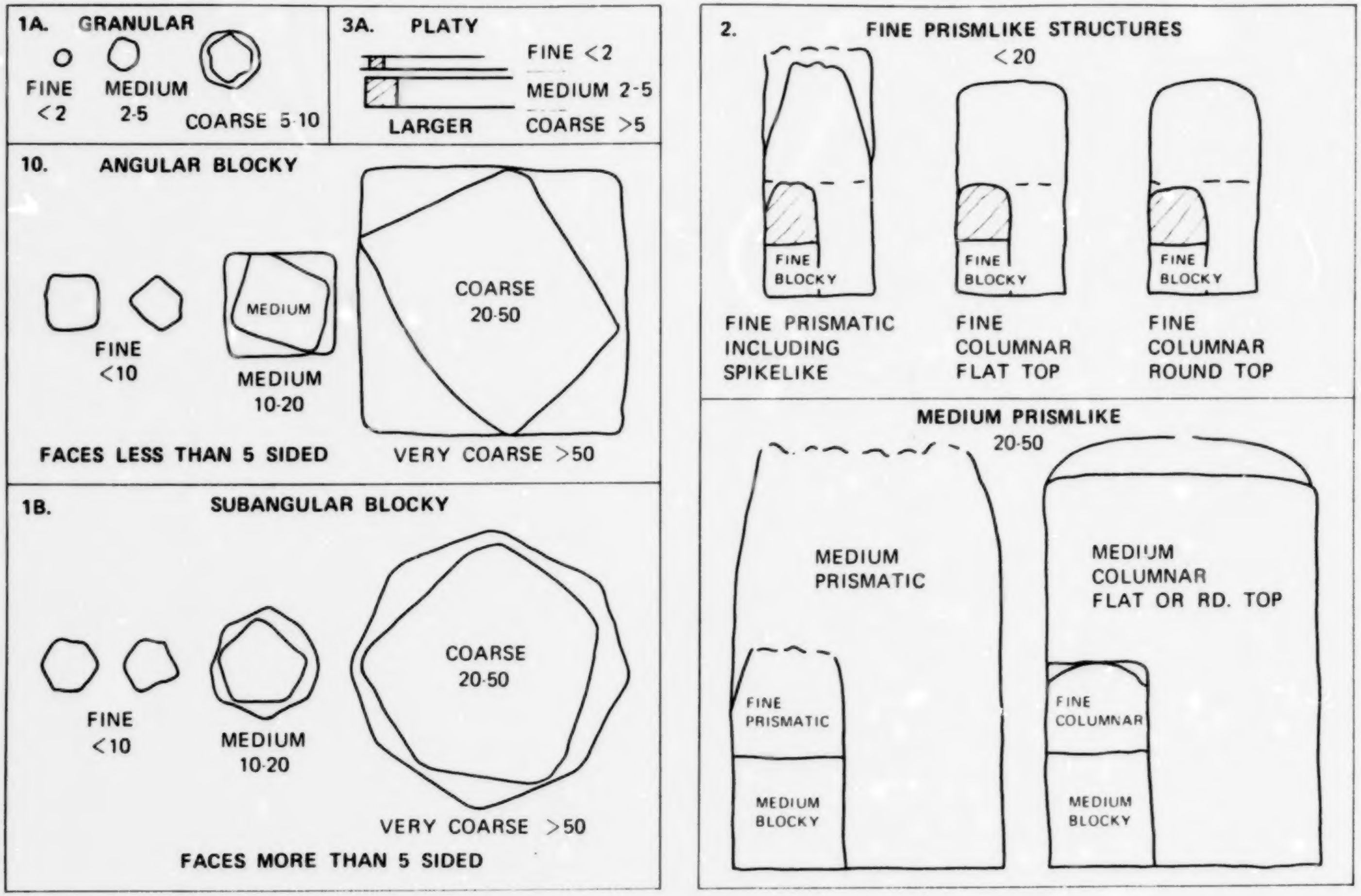
1A. GRANULAR
FINE <2
MEDIUM 2-5
COARSE 5-10
3A. PLATY
FINE <2
MEDIUM 2-5
COARSE >5
LARGER
10. ANGULAR BLOCKY
FINE <10
MEDIUM
MEDIUM 10-20
COARSE 20-50
VERY COARSE >50
FACES LESS THAN 5 SIDED
1B. SUBANGULAR BLOCKY
FINE <10
MEDIUM 10-20
COARSE 20-50
VERY COARSE >50
FACES MORE THAN 5 SIDED
2. FINE PRISMLIKE STRUCTURES
<20
FINE BLOCKY
FINE BLOCKY
FINE BLOCKY
FINE PRISMATIC INCLUDING SPIKELIKE
FINE COLUMNAR FLAT TOP
FINE COLUMNAR ROUND TOP
MEDIUM PRISMLIKE
20-50
MEDIUM PRISMATIC
FINE PRISMATIC
MEDIUM BLOCKY
MEDIUM COLUMNAR FLAT OR RD. TOP
FINE COLUMNAR
MEDIUM BLOCKY

Figure 22. Diagrammatic representation of some of the types, kinds, and classes of soil structure. (Source: Expert Committee on Soil Survey 1983).

subgroup, soil
A category in the Canadian system of soil classification. These soils are subdivisions of the great groups, and therefore each soil is defined more specifically.

subsoil
The B horizons of soils with distinct profiles. In soils with weak profile development, the subsoil can be defined as the soil below the plowed soil (or its equivalent of surface soil) in which roots normally grow.

surface expression
The form, or assemblage of slopes, and pattern of forms of genetic materials. Examples are undulating, level, hummocky, ridged, ribbed, and so forth.

swamp
A peat-filled area or a mineral wetland with standing or gently flowing waters occurring in pools and channels. The dominant peat materials are shallow to deep mesic to humic forest and fen peat formed in an eutrophic environment resulting from strong water movement from the margins or other mineral sources.

terrestrialization
Formation of a mire system by filling of a water body with organic remains, usually by gradual extension of peat-forming communities outwards from the shoreline of a lake.

terric layer
An unconsolidated mineral substratum underlying organic soil material.

texture, soil
The relative proportions of the various soil separates in a soil as described by the classes of soil texture. The limits of the various classes and subclasses are given below and are shown in Figure 23.

sand - Soil material that contains 85% or more sand.
loamy sand - Soil material that usually contains 70 to 85% sand but may contain as much as 90% sand depending upon the amount of clay present.
sandy loam - Soil material that usually contains 52 to 70% sand but may contain as much as 85% and as little as 43% sand depending upon the amount of clay present.
loam - Soil material that contains 7 to 27% clay, 28 to 50% silt, and less than 52% sand.
silt loam - Soil material that contains 50% or more silt and 12 to 27% clay, or 50 to 80% silt and less than 12% clay.
silt - Soil material that contains 80% or more silt and less than 12% clay.
sandy clay loam - Soil material than contains 20 to 35% clay, less than 28% silt, and 45% or more sand.
sandy clay - Soil material that contains 35% or more clay and 45% or more sand.
silty clay - Soil material that contains 40% or more clay and 40% or more silt.
clay - Soil material that contains 40% or more clay, less than 45% sand, and less than 40% silt.
heavy clay - Soil material that contains more than 60% clay.

till
Unstratified glacial drift deposited directly by the ice and consisting of clay, sand, gravel, and boulders intermingled in any proportion.

topography
The physical features of a district or region, such as those represented on a map, taken collectively; especially the relief and contours of the land.

undifferentiated
A layered sequence of more than three types of genetic material outcropping on a steep erosional escarpment.

void
Space in a soil mass not occupied by solid mineral matter. This space may be occupied by air, water, or other gaseous or liquid material.

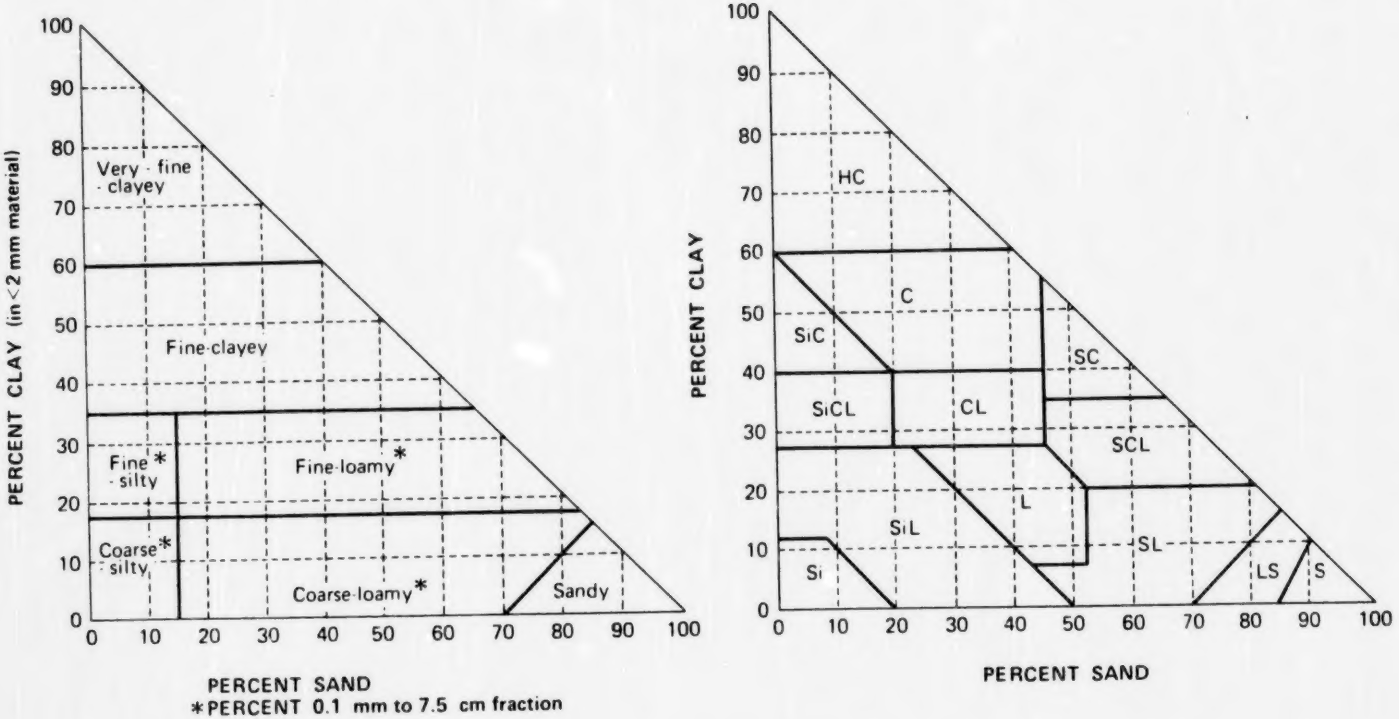

Figure 23. Family particle size classes and texture classes shown in terms of percentages of sand and clay. (Source: Expert Committee on Soil Survey 1983).

water table
The upper surface of groundwater or that level below which the soil is saturated with water.

weathering
The physical and chemical disintegration, alteration, and decomposition of rocks and minerals at or near the earth's surface by atmospheric agents.

wetland
Land having the water table at, near, or above the land surface or which is saturated for a long enough period to promote wetland or aquatic processes as indicated by hydric soils, hydrophytic vegetation and various kinds of biological activity which are adapted to the wet environment.